PROFILES IN SCIENTIFIC RESEARCH CONTRIBUTIONS OF THE FELLOWS

VOL-III

DIAMOND JUBILEE PUBLICATION
(1995)

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DIAMOND JUBILEE

INDIAN NATIONAL SCIENCE ACADEMY
Bahadur Shah Zafar Marg, New Delhi - 110 002

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Foreword

The Indian National Science Academy is celebrating its Diamond Jubilee during 1994-1995. To mark this occasion, a series of seminars, symposia and special lectures on subjects of great concern to Indian scientists have been organized at INSA premises as well as in Local Chapters all over the country. In addition, status reports on specialized topics of great relevance have been brought out. In this connection, 14 special volumes have been published by the Academy. It was thought desirable to have documents of great value presenting contributions of the Fellowship. A two-volume *Compendium* brought out in January, 1994 gives a brief account of the biographical matters, career profiles, major contributions in keyword form, honours and awards received by the Fellows. The present five-volume set of Profiles is devoted entirely to the highlights of research contributions of the Fellows.

I am very glad that the Fellowship has responded enthusiastically to our invitation to provide the necessary inputs. More than 80% of the Fellows have contributed. As a result, the Profiles now comprise of five volumes rather than the two volumes brought out by the Academy at the time of the Golden Jubilee Celebrations 10 years ago. The first three volumes cover Physical Sciences whereas the other two cover Biological Sciences. Eventhough the volumes are limited to the contributions of Fellows of the Academy, they represent, in a way, national contributions to all branches of science and technology. These are meant to serve as reference material for researchers interested in study of development of science in India.

I have great pleasure in recording my admiration of the untiring efforts of the editors, Dr Krishan Lal and Prof RN Kapil, who have taken great pains in editing the Profiles. I appreciate the contributions of Shri SK Sahni, Executive Secretary and Dr Alok Moitra, Officer on Special Duty, Diamond Jubilee Celebrations, who meticulously coordinated the entire work and ensured that the schedule of publication was maintained as planned. Aakriti Graphics, the printing press has acted as a part of the team showing high level of cooperation and concern for quality. There are several other devoted individuals whose efforts have been considerable but it is not possible to thank them individually.

I hope this series of Profiles will be valuable to the scientific community.

January 1, 1995
New Delhi

SK Joshi
President
INSA

Preface

It gives me great pleasure to present volume I-III of the Profiles of the Fellows of the Indian National Science Academy as a part of the Diamond Jubilee Celebrations. The response of the Fellowship to our request was very encouraging. Nearly 80% of all Fellows have either contributed fresh write-ups or allowed us to use profiles available in the series brought out at the time of Golden Jubilee with required modifications. As a result, Physical Sciences (Sectional Committees I-V) are spread over three volumes. The first volume has profiles of Fellows specialising in Mathematics and Physics; the second volume is devoted to Chemical Sciences and the contributions of Fellows with Engineering, Technology and Earth Sciences as specialisation are covered in the third volume.

The editorial work of manuscripts was not a simple task as anticipated. Each of the Fellows is an eminent personality in his own right and has his own characteristic style and perception for his profile. However, an attempt has been made to ensure a broad uniformity. Therefore, at times, information, though important, on biographical details, honours, awards, citations etc. had to be left out, keeping in view the fact that this series is complementary to the *Compendium of Fellows of the Academy*. Nevertheless, the style of presentation of the original manuscripts has been retained. Most of the Fellows, including the seniormost, accepted our request gracefully to restrict the number of references to their published work to 15 only. However, in very few cases, this had to be done editorially. Attempt has been made to ensure that no important publication is left out.

I enjoyed thoroughly the task of processing the manuscripts. It is indeed inspiring to go through the high level of research attainments of the elite of the Indian science. I am confident that the Profiles will stand out as a landmark publication giving valuable information to all concerned with Indian science during the last 50 years or so.

It is with great warmth and pleasure that I record my appreciation of the untiring efforts of Shri SK Sahni, Executive Secretary and Dr Alok Moitra, Officer on Special Duty, who have been on their toes to ensure the timely publication by the press. The technical support received from Shri Tarun Banerjee and Shri Javed Khan has been of great value. This publication was not a usual volume and we were trying to accommodate as many profiles as possible. The last one being just a week before printing started. Aakriti Graphics (press) had to accept such and other difficult requests at short notices

causing considerable deviations in the course of their work. I appreciate the spirit with which they have completed this work.

It is my hope and wish that this series of volume will be widely used and act as a reference material.

January 1, 1995
New Delhi

Krishan Lal
Editor

Contents

SECTIONAL COMMITTEE — V

SECTIONAL COMMITTEE — IV
Engineering and Technology
Applied Physics, Chemical Technology, Electronics & Telecommunication Engineering and Engineering Sciences

Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
Diamond Jubilee Publication, INSA, New Delhi, 1995.

Kadavil Poulose Abraham

High temperature metal extraction processes such as iron and steel making and copper smelting have been developed over the years mostly on empirical basis. It was after the second world war that serious attempts were made to understand the physico-chemical principles underlying the high temperature metal extraction and refining processes. Beginning from the 1940s much work was done by several research groups on the measurement of fundamental thermodynamic and kinetic data relevant to reacting system encountered in high temperature extractive metallurgy. The research and development contributions of Abraham belong to this category and he has made significant contributions to the understanding of the fundamentals of some of the high temperature extractive and refining processes.

The main areas of research and development work carried out by Abraham can be classified under the following heads:

(1) Measurement of thermodynamic properties of silicate melts of interest in iron and steel making by gas equilibration techniques and calorimetry.

(2) Investigations on the thermodynamic properties of (a) binary metal oxide systems and (b) oxygen dissolved in liquid copper alloys by the high temperature solid electrolyte galvanic cell technique.

(3) Studies on the kinetics of gas-solid reactions by thermogravimetric techniques.

(4) Development work on the electroslag refining of steels and non-ferrous metals.

Thermodynamic properties of silicate melts

Abraham carried out research in this area in the 1950s as a member of the Nuffield Research Group in extraction metallurgy at Imperial College, London.

Formerly, Professor & Chairman, Department of Metallurgy, Indian Institute of Science, Bangalore 560 012; *Residence :* 10, Walker Lane, Richmond Town, Bangalore 560 025.

The work carried out included measurement of (a) MnO activities in binary and complex silicate melts at iron and steel making temperatures (1400-1700°C) and (b) sulphur holding capacities of silicate melts of interest in iron and steel making.

The thermodynamic activity of MnO in the melts was studied by equilibrating the melts with a gas phase of known oxygen potential and a Mn-Pt alloy of known Mn activity. The data collected[1,2] are useful in predicting the behaviour of manganese under a variety of iron and steel making conditions.

Sulphur is a deleterious element in steels and for a variety of applications, its concentration has to be brought down to very low limits and in some cases to parts per million levels. The sulphur holding capacities of a number of silicate melts were measured by equilibrating the melts with a gas phase of known oxygen and sulphur potentials and quantitative data[3] on conditions for transfer of sulphur to the slag were obtained.

The thermodynamics of mixing of binary silicates when they formed ternary melts was studied by solution calorimetry. The results obtained showed that in the systems studied, the enthalpy contribution to the mixing processes was negligibly small[4,5] in conformity with the theory of ideal mixing of silicate melts, according to which the main contribution to the free energy of mixing is the configurational entropy of mixing of the cations.

Thermodynamic measurements with high temperature solid electrolyte galvanic cells

The early work on defect ionic crystals particularly on stabilized zirconia and doped thoria laid the foundation for a systematic study of solid electrolytes. By the late 1950s it became known that these defect ionic crystals could be used as solid electrolytes in high temperature galvanic cells for the measurement of oxygen potentials and began to be used for a variety of applications. Studies were initiated by Abraham in the Department of Metallurgy, Indian Institute of Science, Bangalore to use this new technique for (a) measurement of metal oxide activities in oxide solid solutions, (b) evaluation of free energies of formation of oxide compounds and (c) studying the influence of alloying elements on the thermodynamic activity of oxygen dissolved in liquid copper.

The properties of a number of binary oxide solid solutions were investigated by this technique using lime zirconia, thoria yttria and calcium fluoride single crystals as solid electrolytes. These studies gave an understanding of the relative influence of ionic size disparity, electronegativity and crystal field stabilization effects (in the case of oxides of transition metals) on their mixing

behaviour. The calcium fluoride single crystal solid electrolyte was also used for measuring the free energies of formation of a number of oxide compounds[6,7]. A notable development has been the measurement of the standard Gibbs energies of formation of platinum rich intermetallic compounds in the systems Pt-Mg, Pt-Ca and Pt-Ba using solid state galvanic cells based on Mg_2, CaF_2 and BaF_2 as solid electrolytes[8].

In the case of metal refining, one deals with impurities at low levels and the interaction between solutes at low concentrations in a solvent metal is of great significance. The Wagner interaction parameter which is a measure of the interactions at low concentrations, is of value to the refiner. The effect of adding small quantities of cobalt, nickel, iron and manganese on oxygen dissolved in liquid copper was studied using the high temperature galvanic cell technique and the corresponding Wagner interaction parameters were evaluated[9,10].

Kinetics of gas-solid reactions

Roasting of metal sulphides in air, hydrogen reduction of metal oxides, chlorination and hydrochlorination are example of metallurgically important gas-solid reactions. Identification of control mechanisms of these gas-solid reactions is useful in the design of reactors. Abraham carried out kinetic studies on a few identified systems by thermogravimetric techniques. A novel feature was the provision made for the simultaneous measurement of temperature changes occurring within the reacting solid. The studies have contributed to an understanding of the interplay of heat and mass transfer in controlling the reaction rates[11,12].

Developmental work on electroslag refining

Electroslag refining is a secondary remelting process designed for producing quality steels and alloys required for specialised applications needed by the nuclear, aerospace, power generation and aircraft industries. In this process the commercially produced metal is refined with the help of a reactive slag kept molten by the ohmic heat generated when a heavy current passes through it. Though the process was developed abroad much earlier, it was only in the mid-sixties that work in this area was initiated in India. A laboratory scale electroslag refining unit was designed and constructed in the Metallurgy Department of the Indian Institute of Science, Bangalore and based on the experience gained a larger unit capable of producing steel ingots 200 ml in diameter was fabricated. The units were used to study the control mechanisms in the transfer of elements like manganese and chromium between the electrode and slag at the high operating temperatures (1500-2000°C). They were also used to collect data on the slag

compositions to be used for the refining of a variety of steels and non-ferrous metals. Separate studies were made to assess the improvement in mechanical properties brought about by the remelting process[13,14]. The unit has also been used for studies on the electroslag casting of intricate shapes.

Abraham has written a text book on non-ferrous extraction metallurgy with H S Ray and R Sridhar as coauthors[15].

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
Diamond Jubilee Publication, INSA, New Delhi, 1995.

Tanjore Ramachandra Anantharaman

Starting with his doctorate work at Oxford University in 1951 as the only Rhodes Scholar for that year from India, Anantharaman has been continuously engaged in metallurgical research for over four decades now, first as Post Doctoral Fellow at the Max-Planck-Institut für Metallforshung, Stuttgart (1954-1956), then as Assistant Professor of Metallurgy, Department of Metallurgy, Indian Institute of Science, Bangalore (1956-1962), then as Professor of Metallurgy, Department of Metallurgical Engineering, Banaras Hindu University, Varanasi (1962-1987), then as Director, Thapar Corporate Research and Development Centre, Patiala (1989-1992) and finally as CSIR Emeritus Scientist, National Physical Laboratory, New Delhi (1992 to date). He took active steps to establish a doctoral programme in an engineering discipline at Varanasi when technological research in general and metallurgical research in particular were still in their infancy in India.

Anantharaman was able to establish active Schools of Research in:

(1) Structural imperfections in metals and alloys

(2) Structural changes in metals and alloys

(3) Structure of rapidly solidified alloys

Structural imperfections in metals and alloys

In the course of the last five decades, it has come to be generally accepted that structural imperfections like vacancies, dislocations and stacking faults, in spite of their small number in relation to the total volume of the solid, largely determine the mechanical behaviour of solid metals and alloys. Among these types of defects, dislocations and stacking faults are amenable to study by the X-ray diffraction technique, as they affect X-ray reflections in several ways. Anantharaman and his co-workers have contributed significantly to the development of theoretical treatments for the X-ray diffraction effects of stacking

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faults as well as to their application for experimental evaluation of imperfections in several metals and alloys.

One of Anantharaman's early contributions in this field emerged from his doctorate work at Oxford and dealt with a new method for measuring integral breadths of X-ray reflections[1]. Subsequently, a general method of analysis for separation of domain size, lattice strain and stacking fault contributions from X-ray breadths of face centred cubic (fcc) metals was developed by this group. Along with one of his students, he developed a modified Fourier method of analysis using a single X-ray diffraction line to overcome the limitations of the well-known Warren-Averbach method, wherein multiple orders of X-ray reflections are required. From his doctorate work on cobalt, he had earlier postulated for the first time that in hexagonal close packed (hcp) crystals two types of stacking faults, viz., growth and deformation faults, could co-exist[2].

Later, Anantharaman and his group at Varanasi dealt with a third type of fault (extrinsic fault) in hcp structures and developed the necessary X-ray diffraction theory[3]. He also pointed for the first time[4] that in the presence of particles of different sizes in cold-worked filings, asymmetry in peak displacements could occur in X-ray powder reflections due to different extent of deformation faulting in filings of different grain sizes.

An important theoretical development to the credit of the Varanasi group concerns possible fault configurations in double hexagonal close-packed (dhcp) crystals as well as the calculation of X-ray diffraction effects in such faulted structures[5]. A variety of plastically deformed metals[6] and alloys and, for the first time, rapidly solidified alloys, were subjected to X-ray studies for imperfections by the Varanasi researchers and measurements of the stacking faults in them were carried out. Such X-ray studies on plastic deformation have encompassed a large number of pure metals with fcc, hcp and body-centred cubic (bcc) structures and alloys with fcc, hcp, dhcp and bcc structures.

Structural changes in metals and alloys

A knowledge of phase transformations in general and structural changes in the solid state in particular in different alloys is the foundation on which the modern science and technology of alloys development and processing has been built over the last few decades. The contributions of Anantharaman and his students in this field have revolved round the establishment of binary phase diagrams, the study of precipitation reaction in alloys and the investigation of tempering response in low-alloy steels.

At Varanasi, X-ray precision studies of copper-zinc alloys led to the exact determination of the solvus curve between the terminal fcc phase and the next bcc phase in that alloy system. Among the binary phase diagrams, the manganese-gallium system (Mn-Ga) is characterized by the combination of a very high melting metal with a very low melting metal. Anantharaman's work at Stuttgart during an extended visit in collaboration with German researchers led to the identification of eight peritectic, three eutectoidal and two peritectoidal reactions as well as ten intermetallic phases[7] in the Mn-Ga system. An explanation for the complexities in the electrical resistivity and super-conductivity on annealing at sub-zero temperatures of alloys in the cadmium-mercury system, based on order-disorder transformations, was suggested[8] by him during a short visit to the San Diego campus of the University of California, USA.

Anantharaman has had an abiding interest in the study of precipitation hardening in aluminium alloys, partly because of the vast resources and potential for aluminium alloy development in this country. Extensive investigation of the precipitation reactions in aluminium-zinc alloys by his group led to a study of side bands[9] in their X-ray patterns and metastable solvus curves[10] in their phase diagram. Based on researches at the Imperial College, London, an explanation for the growth rate in the cellular reaction in Al-Zn alloys was offered by him [11] based on Turnbull's theory of cellular reaction as controlled by cell boundary diffusion and influenced by continuous precipitation in the matrix.

Studies in Varanasi on the simultaneous effect of temperature and deformation on structural changes in commercial aluminium led to the identification of three temperature regions where ductility minima occur. These have been associated with the precipitation of Si, Al, Fe and a metastable bcc Al-Si-Fe phase.

Structure of rapidly solidified alloys

Rapid solidification of metals and alloys introduces several metastable effects in their constitution and structure, resulting in the development of unusual chemical, physical and mechanical properties in them. Though it has been known for a long time that the metastable state contributes to improvement in the mechanical properties of alloys, as in martensitic transformation and precipitation hardening, the potentialities of the metastable state could not be realised or exploited fully until the introduction of the 'gun' technique for rapid solidification by Pol Duwez at the California Institute of Technology, USA, in 1939. Following an extended visit to USA in 1965, Anantharaman pioneered research in this fast expanding new field in India.

The contributions of the Varanasi group led by Anantharaman have been in the areas of (a) development of techniques for rapid solidification[12], (b) estimation of cooling rates, (c) production of new non-equilibrium phases and determination of their crystal structure through X-ray and electron diffraction techniques, (d) study of micro-structure, (e) construction of metastable equilibrium diagrams, (f) theoretical postulation to predict the formation of metastable phases, and (g) production and characterization of metallic glasses. One of the earliest and most comprehensive reviews in this area was prepared by Anantharaman and Suryanarayana[13]. About 25 new metastable phases have so far been discovered in Varanasi in rapidly solidified alloys and their crystal structures determined by X-ray and electron diffraction techniques.

As part of a National Project on Metallic Glasses, a unit on metallic glasses was set up at Varanasi in 1982. Anantharaman and his co-workers successfully developed during 1982-1985 the production technology for iron-base alloy amorphous ribbons of up to 5 cm width in this unit.

In the last few years, Anantharaman has been trying to advance an explanation for the complex phenomenon of quasi-crystals, which are easily produced by rapid solidification of some binary, ternary and quaternary alloys based on aluminium, within the framework of traditional crystallography. He has developed a model[14] for the crystallization clusters in alloy melts and has applied the same with some measure of success to the formation of icosahedral and decagonal phases in aluminium-manganese alloys[15].

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Dara Pirojshaw Antia

Antia has a strong background in metallurgy and materials science as well as in mineral economics and industrial management. His multidisciplinary approach combined with long experience in management of industries makes him unique in applying science to practical industrial applications.

Tempering of steels

Understanding of transformation of austenite (the high temperature phase in steels) in solid state in carbon and alloy steels is the basis of heat treatment of steels and their varied properties. He joined hands with Morris Cohen and his colleagues in early forties at Massachussetts Institute of Technology (M.I.T.), Cambridge, Mass, U.S.A. to study the kinetics of tempering of steels in a systematic way. Since there was no known method of determining the amount of retained austenite present, when steels were quenched from high temperatures, an X-ray diffraction method was evolved to determine the amount which involved measurement of intensity of diffraction lines.

The transformation of retained austenite subcritical temperatures was studied by various methods including X-ray diffraction, hardness, microscopic examination and magnetic methods. A special method and instrument was devised to measure the magnetic properties. The results were correlated and new light was thrown on the phenomena of tempering. With this pioneering work subsequent studies by various workers at MIT and elsewhere has helped in the better understanding of the complex nature of phase transformation in the solid state.

Nucleation and grain growth in zinc alloys

Since alloys of zinc are used in various industries such as dry cells, photoengraver plates, addressograph plates, etc., studies were undertaken to find which elements nucleate zinc during solidification. Control of grain size in zinc alloys for various applications cited above is very essential. Studies undertaken at the Zinc Rolling

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Mill of Union Carbide India Ltd., under the guidance of Antia enabled successful development and manufacture of complex zinc alloys for industrial applications for the first time in India.

Contribution to industrial research development and management sciences

Antia's role in development and research in ferrous and nonferrous metals manufacture is outstanding both as advisor to the Government of India after World War II and in helping establishment of National Metallurgical Laboratory and Defence Metallurgical Research Laboratory. He initiated and helped in many projects in both the laboratories and was also Chairman for many years of the Metals Development Council where he helped promote both primary and secondary manufacture of basic metals, alloys and their semimanufactured products.

As early as 1946 in order to make industry conscious of how dependent it is on research and development Antia founded, organised and dedicated a life time's work in establishing and helped in running the Indian Institute of Metals, which is now a premier International Professional and Research Organisation. He also founded and nurtured the Indian Copper Development Centre and The Indian Lead-Zinc Information Centre which are rendering yeomen service to industry both in technical knowhow and research and with which he is intimately associated over the last twenty five years.

Having realised that management skills were necessary and essential to run any research, industrial or educational organisation, Antia not only attended management courses himself (he is a graduate of the Advanced Management Programme of Harvard Business School) but helped in promoting the Calcutta Management Association as well as the Management Development Institute at Delhi. He has published many papers on various aspects of management with particular reference to transfer of foreign technology and transaction of basic research into industrial technology.

Studies and Research on phase equilibria

The major materials used in industry are metals and alloys. Their properties and uses depend upon the alloying elements used, whether metallic or non-metallic and the influence they exert on the structure and phase relationship at different compositions, temperatures, pressures, etc. Alloy phase diagrams are therefore the most important reference guides for all problems in manufacturing, fabricating, heat treatment and research on alloy development, etc. Since data and research work on phase diagrams is not adequate, a world wide effort and organisation to

generate the data became essential. Antia under the auspices of the Indian Institute of Metals initiated the formation of the Alloy Phase Diagrams International Commission (APDIC) which has members from almost all industrial and developing countries. Each country has undertaken to study either binary, ternary or higher order systems of different categories, so that the work is divided and duplication avoided. Antia is the Chairman of the Indian Programme and helps and monitors the Indian part of the International Commission's work. Antia is still active in this programme along with his colleagues in different research centres in India.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
Diamond Jubilee Publication, INSA, New Delhi, 1995.

Vallampadugai Srinivasa Raghavan Arunachalam

Basic Sciences

On ordering and mechanical properties

Arunachalam started his research career in metallurgy at the Bhabha Atomic Research Centre with studies on the X-ray analysis of line broadening effects arising from cold work in nuclear materials such as uranium and thorium. He subsequently obtained his doctoral degree from the University of Wales, with research on the nature of ordering and its effect on mechanical properties in a classic prototype system, CuAu. He established the relationship between microstructure and the mechanism of transformation and was able to relate the origin of the transformation twinning to the stresses arising out of the tetragonal distortion of the lattice that occurs during ordering. He perfected techniques of single crystal growth in this system and explained the nature of work hardening in ordered CuAu. The relationship between transformation stresses, microstructure and mechanical behaviour led to his discovery of the 'stress-induced plasticity' effect, in which the application of stress during ordering in single crystals of CuAu was shown to lead to very high plasticity in an otherwise low ductility material. These studies together constitute one of the first detailed investigations into the mechanical behaviour of non-cubic ordered alloys, an area of research which has proved to be of great importance for the development of engineering alloys based on inter-metallics.

Hydride formation in nuclear materials

Subsequently Arunachalam investigated the nature of hydride formation in zircaloys and its effect on mechanical properties in order to understand well known hydrogen embrittlement phenomena that occur during the service of such nuclear materials. This work led to the definition of the crystallographic features

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associated with hydride formation in zirconium alloys and continues to be cited by the literature in this area to date.

Deformation mechanisms in materials at high temperatures

Arunachalam's research interests in materials, over the last two decades, cover a broad spectrum of work related to the mechanisms of deformation of materials at high temperatures. He has examined the nature of thermally activated process in hexagonal metals like thorium and hafnium. His work on the creep behaviour of dispersion hardened materials led to a significant improvement in the level of understanding of the basic operative mechanism. Stress relaxation experiments and modelling clearly showed that a 'threshold stress' has to be overcome before creep can occur in such particle strengthened materials. The incorporation of such a threshold stress of the right magnitude and correct functional dependence on stress and temperature in the power law creep equation removes the anomaly of inordinately high activation energies and stress exponents contained through the analysis of experimental data by the unmodified power law equation. At about the same time, the experiments to incorporate rare earth oxide particles into titanium as a means of dispersion strengthening were carried out for the first time. These showed that significant strengthening could be obtained, but that the dispersoids were unstable at high temperatures, a conclusion that remains true today, inspite of very extensive efforts to develop titanium alloys with such strengthening mechanisms.

Creep processes also contribute significantly to consolidation densification of powder compacts at high pressures and temperatures. The presence of porosity in the starting compact introduces a high level of complexity into the modelling of such processes, since the stress distribution within the material under external press would be non-uniform. Arunachalam and his colleagues developed an elegant analysis of this problem to show that the problem very simply resolves into using an effecting stress intensification to account for the effect of porosity. Subsequently, a more detailed finite element modelling exercise confirmed the model and in addition brought out the critical role of particle sliding in the densification process. The understanding of consolidation mechanism is of great importance in near-net-shape processing powder metallurgy based components through hot isostatic pressing operations.

Arunachalam and his colleagues have extended this research to evaluate the 'effective modulus' in this class of materials, which helps in detailed engineering analysis. Metal-matrix composites are now being studied by this group using a detailed and comprehensive computer model developed by them.

Research and development to technology

As the Director of the Defence Metallurgical Research Laboratory, Arunachalam initiated major R & D programmes, some of which were brought to maturity and the production phase even while he was the director of the laboratory.

Armour and ammunition

Of the latter category are the powder metallurgy based production technology for brake pads of aircraft, which are composites of friction materials. The manufacturing processes for these components were developed at the laboratory at a critical period of extreme shortages within a very short time span. Kanchan composite armour for battle tanks was conceived and developed for protection against combinations of different types of attacks, such as kinetic energy, jet and momentum based threats, and has been accepted by the Army for induction into its battle tanks. It ranks amongst the premier varieties of this class of armour. Monolithic steel armour, developed and tested by the laboratory during his tenure, now armours many paramilitary and military personnel carriers and is used as body armour by Indian paramilitary forces. On the other side of the coin, programme for the development of long rod kinetic energy ammunition based on heavy tungsten alloys were started. Today, a fully automated manufacturing facility with robots, the Heavy Alloy Penetrator Project at Tiruchirapally, has the capacity to mass produce these ammunitions.

Aeronautical materials

Anunachalam also launched a strong technology initiative into aeronautical materials centred around investment casting processes for directionally solidified and single crystal aerofoil shapes of nickel-base alloys and powder metallurgy based processes of atomisation and not isostatic pressing to near net shapes. The naturally longer gestation periods for the evolution of aeronautical materials and processing technology meant that these initiatives were translated into actual hardware for critical miscible and aeronautical application in the late eighties and early nineties.

Titanium

While India has the largest resources of limenite, an ore of titanium in the world, and manufacturing facilities for mill forms of titanium and titanium alloys exists, a gap in India's technological capability in the ore to product cycle is the extraction of titanium metal from its ore. A pilot plant for the extraction of titanium from its ore by the Kroll process, based on technology developed at the Bhabha Atomic Research Centre, was conceived and the project launched. This

plant has been run successfully at the 1 ton per batch level, and based on this demonstration, the production of titanium at a 1000 ton/year level has been conceived.

Management of defence research and development

In 1982, Arunachalam was appointed as Scientific Adviser to the Defence Minister and the Director General of the Defence Research and Development Organisation. During his tenure as Chief executive of India's 40 and odd defence laboratories, the organisation realised significant successes in conceptualising, in designing, developing and manufacturing hardware for major warfare systems. The integrated guided missiles programme covering a range of capabilities with its 5 missile systems, and the main battle tank, Arjun, are the outstanding examples of weapons systems which have been successfully concluded under his stewardship. The ambitious Light Combat Aircraft Programme was also initiated in the early phase of his tenure and the first prototype is expected to fly in the late nineties.

Apart from his direct responsibilities in defence, Arunachalam has also been instrumental in recommending a list of non-military technology missions for the country and was advising the Prime Minister in these areas for more than a decade. These cover a wide spectrum of programmes ranging from communication networks to the immediate and immense problems of providing potable water, mass education and primary health care in rural India.

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Anand Swarup Arya

The essential steps in a scientific approach to the design of engineering structures for resisting safely the imposed seismic ground motions are: (i) a realistic estimation of the ground motion parameters, viz. the earthquake magnitude, its focal depth and epicentral distance, and the intervening soil medium, using which a probable accelerogram is to be worked out in a given design life period at the base of the structure, and (ii) a dynamic response analysis of the structure which should take into account its mass and stiffness distributions, inelastic load-deformation characteristics, energy dissipation through structural and geometric damping, and influence of damage of non-structural elements.

Historically, structural design for earthquakes was started by representing the seismic effect by a lateral force proportional to the weight of the structure applied to it externally like the wind force. The seismic force was taken rather arbitrarily as 1/20th to 1/10th of the weight of the structure. The science of treating the earthquake effects on the basis of the dynamic response of the structure of the ground motion developed in the fifties and thereafter. Arya's research work was mostly in the area of rational seismic response determination and introducing innovations either for increasing the earthquake resistance of structures or reducing the seismic effects themselves. A brief account of his major achievements is given here.

Seismic response analyses

A number of tall structures, namely, chimney stacks, prilling towers, refinery column structures of mixed composition consisting of steel columns and reinforced concrete supporting structures, hyperbolic cooling towers, tall girder bridges, etc. have been analysed rationally by developing an appropriate transfer function type numerical analysis, introducing soil-structure interaction in the Timoshenko beam model wherein shear deformation as well as rotary inertia terms were also included[1-5]. Two examples of these are given below.

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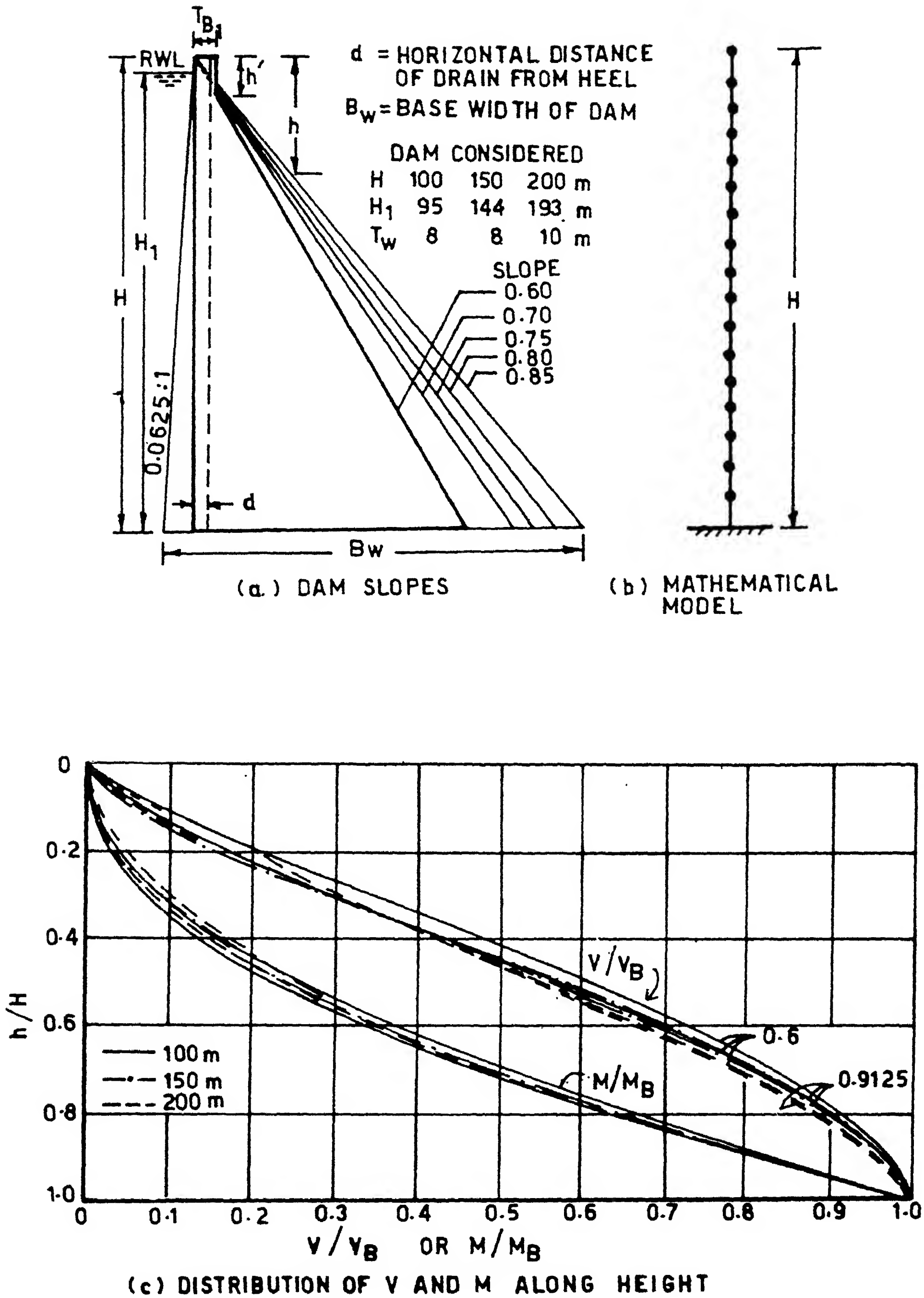

Fig. 1 Seismic response of concrete dams

Effects of face slopes of gravity dams on their response[1]: Fig. 1 shows the dam sections, the stick model and the final results obtained from the parametric study, using $H = 100$, 150 and 200 m, $H_1 = 95$, 144, 193 m, and $B_1 = 8$, 8, 10 m, respectively; upstream slopes = 0, 0.0625, downstream slopes 0.6, 0.7, 0.75, 0.8, 0.85; and reservoir in full and empty conditions. The guidelines for the response calculations of dams were arrived at as follows:

Fundamental period $(T) = 5.55\ (H^2/B)\ \sqrt{\rho/E}$
where ρ is the mass density; and E, the modulus of elasticity of the dam material.

Base shear $(V_B) = 0.6\ W\alpha_h$; and base moment $(M_B) = 0.6\ W\alpha_h\bar{h}$ where W is the total weight of dam; α_h, spectral acceleration for period T and appropriate damping, and $\bar{h}$, height of centre of gravity of the dam above the base. For any horizontal section at a depth h below the top, the seismic shears and moments may be obtained as a ratio of V_B and M_B using Fig. 1c. These results have been incorporated in Indian Standards IS : 1893-1975 for design of dams.

Response of tall refinery column structure resting on pile foundation[3] : The structure, its mathematical model, the mathematical model for the pile and the results obtained are shown in Fig. 2. The base spring of the superstructure, k_y, was obtained by considering the elasticity of the pile soil system, with piles as continuous elements. Piles have been modelled separately, as shown in Fig. 2 using similar analysis. From Fig. 2, the response is seen to be higher for the elastic base as compared with fixed base case, bringing out the importance of soil in the structural response.

Innovative structural systems

Detailed study of earthquake effects on sliding and overturning of freely supported objects during Koyna earthquake of 11 December 1967 and Broach earthquake of 23 March 1970[6,7] provided a novel approach to obtain strong ground motion data; it also gave an understanding of friction-supported structures[8-12] which has been used by Arya in developing new systems of safe and economical structural design. Two examples of masonry buildings are cited here.

Base isolation of brick buildings[8,9] : It was recognized that if the structure is isolated from the foundation through some isolation devices or if a flexible elastic system is introduced between them, the resulting seismic response of the structure is very much reduced. This concept is applied to brick and stone buildings by introducing a break in the masonry bonding and giving a relatively smooth level surface at plinth level. The resistance to sliding against ordinary lateral loads like

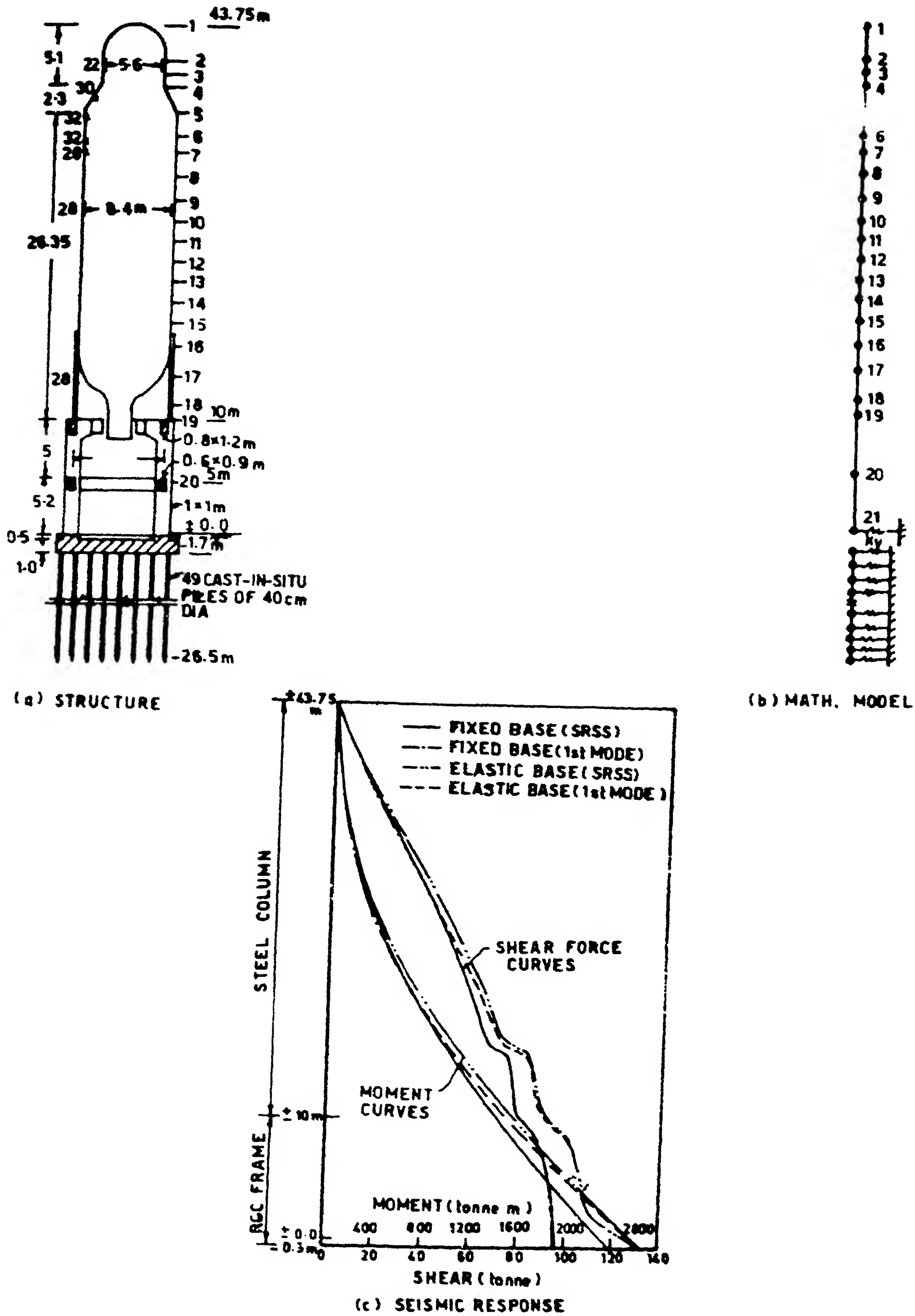

Fig. 2 Seismic response of refiner column structures

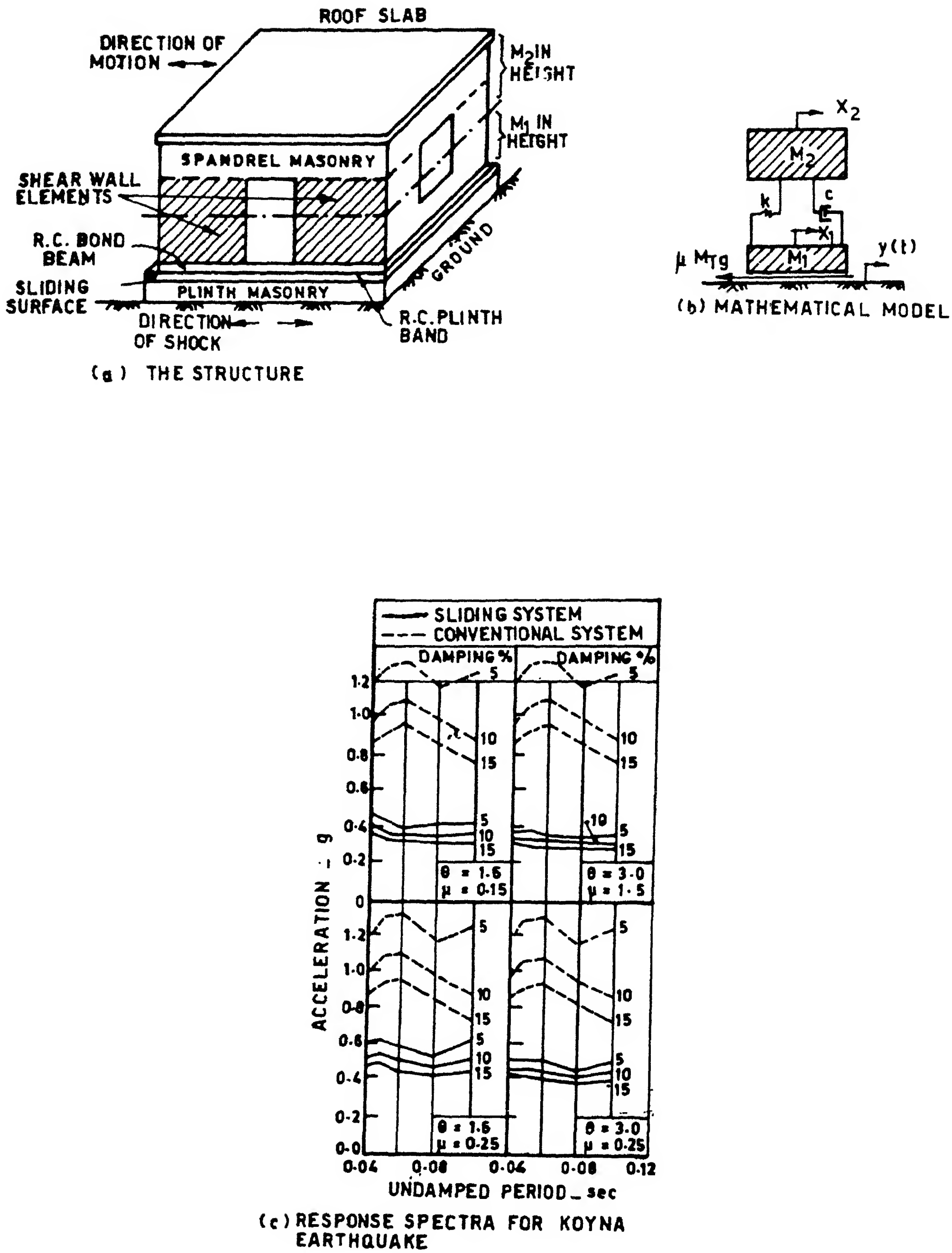

Fig. 3 Sliding concept for masonry buildings

wind and small earthquakes comes from the frictional resistance, but under large earthquakes, the superstructure is free to slide. Non-linear frictional resistance analyses to severe recorded accelerograms as well as shock-table tests of half-size specimens of one room masonry houses on shake table have clearly proved that the system is most efficient when it is most needed, i.e. when the peak ground acceleration coefficient is much larger than the coefficient of friction. Fig. 3 shows the system and some of the results. The frictional response spectra become flat and much below the elastic response spectra. Yet, the largest lateral sliding movement is estimated[9] to remain less than 25 mm.

Half-brick bearing wall construction[3] : Another scheme of brick building construction that would be more economical, and yet more earthquake resistant than the usual constructions, has been developed, analysed and fullsize specimens tested on shake table to prove the scheme. It consists of half-brick thick load bearing walls (11.4 cm thick) with reinforced concrete vertical elements (11.4 cm x 11.4 cm with one bar 12 mm) built with the walls at spacings of not more than 1.5 m. Horizontal reinforcing elements are located at door and window lintel level. The scheme is suitable up to two storeyed buildings, the earthquake resistance being such that such buildings could be used in the severest seismic zones in India, such as the north-eastern region. The saving in cost of civil construction could be as much as 30% as compared with the usual load bearing wall construction.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Srikumar Banerjee

Banerjee has devoted his scientific career in the research area of phase transformations in alloys. In last five to seven years he has focussed attention on (i) clustering and ordering instabilities in solid solutions, (ii) production, characterization and crystallization of metallic glasses, (iii) optimization of fabrication parameters of Zr-2.5 Nb pressure tubes and (iv) the mechanism of shape memory effect in martensitic alloys.

Banerjee's work in the area of phase transformations in alloys covers almost the entire spectrum of solid state transformations encountered in metallic materials. He has made a very comprehensive study on the transformation processes in zirconium alloys and their influences on the mechanical properties of the product. This work includes crystallography of martensitic transformation, thermodynamic prediction of metastable phase reactions and their experimental confirmation, strengthening mechanisms and mechanisms of hybrid transformation processes which combine features of displacive and replacing transitions. Findings of this work which are frequently quoted in current literature are extremely useful in rationalizing the microstructural evolution in zirconium alloys during heat treatment and fabrication steps and in structure-property correlations of these alloys. Banerjee has also applied this approach in successfully optimizing the fabrication parameters for Zr-2.5 Nb pressure tubes currently being fabricated in Nuclear Fuel Complex, Hyderabad.

In recent years, Banerjee has extended his work in the area of phase transformations under conditions far from equilibrium by employing two different techniques, namely, rapid solidification and radiation damage. The former technique has enabled him to explore a number of metastable phases having crystalline, quasicrystalline and amorphous structures. His studies on zirconium base amorphous alloys have encompassed various aspects like glass forming tendency as a function of alloy composition, kinetics and mechanisms of

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crystallization, diffusion mechanisms, mechanical properties and solid state amorphization. This work has provided valuable information on the new class of metallic glasses which do not contain any metalloid elements and has opened up interesting possibilities of use of amorphous alloys in surface modifications and joining of zirconium alloys.

In the area of radiation damage research, Banerjee has made a very systematic study on the influence of radiation on the order-disorder transformation using both electron irradiation and cascade forming heavy ion irradiation. He has demonstrated from both theoretical and experimental work that the direction of the order-disorder transformation can be reversed under radiation environment by a suitable control of the temperature and the dose rate. His theoretical analysis of the kinetics of ordering under irradiation has been verified by him through some elegant experiments.

With the help of *in situ* observations made in a high voltage electron microscope, Banerjee has been able to demonstrate the progress of transformation in real time. His experiments on the order-disorder transition in Ni-Mo alloys have resolved long standing controversies regarding the nature of the short range order and the mechanism of the transition from the short range to the long range ordered state. For the first time he has shown that radiation experiments can be used for obtaining an insight into the mechanism of a phase transformation process.

Banerjee has examined the possibility of describing several transformation processes in terms of one or more concentration waves, displacement waves or their combinations. Evidences in support of the occurrence of first order transitions through the formation and the subsequent amplification of such fluctuations have indeed been obtained in his experiments. His work relating to the superimposition of clustering and ordering instabilities can explain the early stages of the precipitation process in which an ordered intermetallic phase emerges continuously from a supersaturated solid solution.

The question of continuous vis-a-vis discrete (nucleation of growth) modes of ordering in alloys has been addressed to by a number of research groups in their attempts for classifying the ordering process as a transition of the first or the higher order. After the discovery of a class of alloys which, in the short range ordered (SRO) state, exhibits anomalous diffraction maxima, a serious controversy started on the nature of SRO and the mode of transition from SRO to the long range order (LRO). Banerjee's work has resolved this controversy which existed in literature for nearly 25 years. He has established for the first time the

ordering mechanism map in which the order parameter-temperature regimes for different modes of ordering are identified. His work has unified two apparently contradictory descriptions of the SRO state—one involving concentration waves while the other based on a distribution of ordered microdomains. His work has also identified the path through which the SRO state transforms into the LRO state. His subsequent publications in this field has shown how short wave length concentration waves of different wave vectors interfere to produce sub-unit cell motifs of competing superlattice structures. In this context, he has introduced the concept of superlattice tiles and has shown that such tiles representing different superlattice structures can juxtapose to decorate the lattice in periodic or quasiperiodic arrays. In an extension of this work the link between the periodic and the quasiperiodic structures has been established using a projection formalism approach.

The major significance of his work on the evolution of order is that it provides a structural description of the process in which fluctuations (either in concentration or in strain) gets localized through superimposition of corresponding waves of different wave vectors. This gives an insight into the pre-nucleation process of some first order phase transitions.

In the studies on shape memory alloys the contribution Banerjee and his colleagues have made include, (i) determination and rationalization of the reversion stress which develops during the spring back action of a shape memory material, (ii) identification of the role of self-accommodation of transformation strains associated with a group of neighbouring martensite crystals and (iii) reporting and explaining the thermal arrest memory effect.

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Amalendu Bhushan Bhattacharyya

Bhattacharyya has been one of the pioneers of research effort in India in the area of microelectronics. The range of problems addressed by him truly reflects the complexity and dynamic evolution of contemporary microelectronics technology. Starting his research work on the physics and modelling of solid state devices, he envisaged the importance of technology and design. The integration of physics, technology and design makes his research effort comprehensive in character. Further, the work also reflects the perception that ultimately the utility of the work lies in system application. While digital system had been the early beneficiary of micro electronics technology, the real world information is always available only in analogue form. For the useful range of time bandwidth product, there is no unique technological option in signal processing. Bhattacharyya has pioneered research in all the three key options of analogue signal processing—surface acoustic wave device, charge coupled device, and semi-custom analogue gate array.

Charge coupled device has been one of the areas where basic contributions have been made. A new type of area variable MOS capacitor has been invented in which for the first time an electronically programmable solid state capacitor has been implemented[1]. The effective area can be changed by varying the voltage on the gate of a capacitor. The underlying principle involves the concept that in an inhomogeneously doped semiconductor, the inversion layer area of an MOS capacitor can be changed by varying the voltage. The device has been used for capacitive weighting of an electronically tunable transversal filter for signal processing. It has also been demonstrated that the bandwidth of a charge coupled device can be extended by 100% by suitably modifying the clock voltage, where a small barrier may be introduced to arrest the back flow in a CCD at higher frequency, thereby increasing the bandwidth[2].

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The quality of thermally grown gate oxide is one of the most critical issues in CCD technology. In order to improve the lifetime of minority carriers and to passivate the mobile sodium, it is the usual practice to grow chlorinated thermal oxide. It was established for the first time that chlorine oxide introduces shallow traps. These traps have been identified and established by a technique of *C-V* measurements with thermal detrapping[3]. Also, the nature of hole traps has been investigated in chlorinated oxide[4].

Depletion mode MOS transistors fabricated using non-implantation techniques have a wide range of applications in LSI/VLSI structures. A technique has been developed by which the measurement of a single parameter—the output conductance—at suitable operating points could extract the relevant parameters of depletion MOST. The measurement not only gave the best accuracy in predicting implant depth and average doping but also had high sensitivity to error in measurement[5]. In the depletion MOST family, a new mode of high speed MOS operation—punch-through accumulation mode—was predicted with fundamental experimental evidence that in a punch-through situation the work function between the gate and the substrate is not that between the gate and the channel[6].

In the field of surface acoustic wave technology, a new concept of tract changing of surface wave in a piezoelectric solid was introduced by partial illumination of interdigital transducers. The advantage of such an approach lies in the fact that it enables tract changing in weak piezoelectric materials with fewer finger pairs[7]. Although SAW devices are usually fabricated on bulk piezoelectric material, a new dimension can be added if the device could be realized on a silicon substrate. ZnO/Si has been the potential multilayer structure. Unfortunately, the common technique of RF magnetron sputtering of ZnO causes significant radiation damage, introducing instability. A new structure, metal-zinc oxide nitride-silicon dioxide silicon (MZNOS) has been realized, where the nitride layer acts as a barrier to radiation damage. The technology is a significant step towards realization of stable monolithic SAW structure[8]. The physical modelling of SAW configuration in a multilayered medium is quite complex. A novel approach of transmission line analogy brings about orders of simplicity to solve the otherwise complex problem[9]. The approach is also extendable to capacitance extraction of VLSI structures from layout.

The passivation of GaAs for MOS field effect application has been one of the important technological challenges in the development of GaAs-based devices. Unlike Si-SiO_2 structures, MIS structure in GaAs lives with the problem of large surface state density. The work on GaN insulator film on GaAs has

shown that with proper thermal treatment, the above structure would show largely reduced interface state density[10]. The well established Zerbst plot for the determination of lifetime has been extended to make it suitable for characterizing MIS structures on III-V compound, where the passivating insulator is leaky[11].

Bhattacharyya has carried out research on a number of solid state devices—bipolar transistors[12], varactors, punch-through diodes, tunnel diodes and dynamic RAM[13].

Microelectronics being exorbitantly expensive, research proposition is a dilemma for any developing country. While there is no escape from involvement in microelectronics for developing countries, there are judicious options to be embarked upon. Bhattacharyya's present involvement in research on analogue gate array for telecommunication circuit[14] is an experiment towards establishment of the thesis that semicustom approach is the most relevant one in modern high-tech dilemma of developing countries[15].

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Ramballav Chakravarti

Chakravarti was engaged throughout his career on planning, design and construction of river valley works, some of which required special studies. Some of these studies and researches had to be undertaken in cases where major difference of opinion existed. A few of these are discussed here in brief.

Farakka barrage project

On joining the project (on deputation for a limited period for planning and giving a start to the constructions) Chakravarty had first to take a decision about the design of coffer dams to be constructed in the deep part of the river Ganga, on which depended the success of the barrage itself. The comprehensive paper of Karl Tarzaghi on cellular coffer dams indicated that this is the usual procedure adopted in such constructions. Without mentioning any reason, he had, however, admitted that there had been some failures. Since such a failure in the case of Farakka barrage (to be constructed right in the river) would be disastrous, Chakravarty studied the possible causes of failures in the past. His studies indicated that in the Ganga at Farakka this would not be feasible because of the deep scour depths (below the dry weather bed) during the flood season. This would require driving the cellular piles more than 50 ft. His studies also indicated that driving of cells in a circular form would tend to increase in diameter at the bottom (as in a bell-mouth), which would increase the hoop-tension in the pile lines. The pile lines would not be able to take the strain below a certain depth of drive. (Then there would be the likelihood of vortex-flow adjoining). Subsequent studies made by Chakravarty on model piles (cellular design) confirmed the expanding diameter of the cells.

Chakravarty next studied the question of seasonal coffer dams, using single pile line backed by earth embankment. To overcome the difficulty of facing the

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sharp local scour pockets at the forward end of the pile lines being driven, he devised suitable sand dredgers, which would constantly pour in dredged sand in the pocket. He had the dredgers made for the purpose.

After he came back to his parent department under West Bengal Government, the project authorities engaged a team of foreign experts and on their advice decided to go ahead with the cellular coffer dams in the deep part of the river. In 1966, Chakravarty was taken in the Technical Advisory Committee and he raised the question before this committee. The foreign experts could not answer the point raised on the expanding nature of circular cells at the lower ends, nor on the question of effect of vortex flow during the flood season, which in any case was to be faced in the case of each of the cellular coffer dams. The foreign experts expressed the opinion that they would prove their contention on the river itself. This was agreed to by the authorities and a number of cells were set up (just outside the barrage area) during 1967. Also, a single cell was driven near the river bank (drive about 35 ft). The cells in the river bed could not withstand even the first flood. The extracted piles of the single cell indicated that the joints had opened up at about 30 ft depth. After this, the coffer dams were made according to the seasonal design (not to face the flood seasons) and the work was completed in three seasons.

Navigation canal entry

The Design Organization (under the Ministry of Irrigation and Power), in consultation with their navigation expert, laid down that the entry into the canal from the barrage pool should point upstream of the river. Studies made by Chakravarty indicated that under such an arrangement, river vessels would not be able to enter the canal from the river during the flood season. His suggestion for having the canal entry pointing downstream in the river was not readily acceptable to the authorities concerned, but they agreed to have the idea of Chakravarty and their idea tested on models. This was done with three alternatives for the entry pointing upstream in the river; all of them proved unsuccessful. The idea of Chakravarty (based upon his academic studies) proved a success. The latter proposal was then adopted.

Closure of river Piali

In the Sundarbans Delta Project, the proposal is to close all the tidal rivers in the Sunderbans, which have virtually not much of catchment area on the country side.

Piali is a small tidal stream falling into the Melta river (another tidal river). Despite best efforts, the channel could not be closed. Then the help of Chakravarty (who had retired quite about 10 years earlier) was sought. He took one year in studying the problem which proved to be difficult and tricky. For an extensive depth the bed material consisted of organic substances from the estuarine water with some (very fine) silt. This had practically not much bearing resistance. The use of timber piles was ruled out. Even steel or concrete piles were not considered feasible for the depth to be encountered. The caisson method was considered risky because of the likelihood of tilting. Chakravarty studied the reasons of failure in the earlier attempts which mainly depended upon the structural strength of the closure work and not on the foundations. His studies indicated that it would be feasible to take advantage of the slippery nature of the bed material, in sliding down of the bed material, in sliding down of two parts of the first cross-dam (to stop the flow of tides), from the two banks of the river. These were to be built with sand bags crated in nylon netting and laid in bonds like brick masonry. (Any gap left in the centre was to be filled up with dumping similar crates). This would also push out the upper part of the soft bed. The first cross-dam would deteriorate in saline water in a few months and was, therefore, to be supplemented by proper earth dam on the downstream of the sand bag cross-dam. To prevent local subsidence (which would cause failure of the construction), the daily filling was to be kept uniform and extremely small, so that additional load added each day may be taken up by the increased bearing resistance gained due to the gradual squeezing out of the water from the water-logged bed material. Care was also to be taken to prevent vortex flow and deep scour pockets (one of the reasons for earlier failure) being formed. The whole structure was expected to sink slowly along with the construction until requisite bearing resistance was achieved. In actual construction, the sinking was as anticipated from the studies and continued not only during the six months of the filling up work but also for another four months, after which there was an abrupt stoppage of sinking, indicating that full bearing power was achieved. Future observations did not show any further sinkage in the foundations. Thus, a non-conventional procedure developed from his studies proved a success in the form of a simple and cheap method for tackling the problem.

Teesta barrage construction (sheet-piling)

In the late seventies when the construction of the Teesta barrage was taken up, Chakravarty (as Chairman of the High-Powered Technical Committee) faced the first problem of the Project. The Barrage design involved three lines of steel sheet-piling across the river under the floor raft. However, the river bed on the left side showed the existence of medium sized stone boulders mixed up in the sandy bed material. While sheet-piles could be driven by the conventional method where the boulders were sparsely placed, it was not feasible to adopt such a procedure when these boulders were too closely located in the sand. To overcome the difficulty, he advised the engineers to excavate a trench two-feet wide vertically, to the depth required, with the help of a two-feet wide grab excavating bucket and lower the steel sheet piles in position.

The procedure advised was to fill the trenches so excavated with a mixture of Bentonite in water, from the start of the excavation, so that the sides did not cave in the trench. After the trench was so excavated for some length of the pile line, lowering of the sheet-piles were to be started. When the sheet-piles were lowered for some distance, wet-sand was poured through pipes reaching the bottom of excavation, so that the sand filled up the trench from the lower layers. For facility of pouring wet-sand, a large diameter funnel was to be placed at the top of the pipe. The upward filling of the sand would move the Bentonite solution forward into the trenches being excavated further. As these works would advance, the sand filling made earlier were to be consolidated by using vibrators. The work would continue until suitable zones were reached, where it would be feasible to use the usual pile driving method.

Subsidence of the right bank of the Hooghly at Uluberia, Jettighat

In 1988-89 a good 600 ft length of the right bank of the Hooghly at Jettighat subsided with the godowns over the land. Chakravarty took up the investigation work for finding out the cause for the same. The plan showed that the river had a concave bend at the place, which would usually involve erosion of the bank from the toe. No bank erosion had been noticed and the toe was quite stable (might have been due to hard soil). Pre-subsidence bank showed moderate slope and the post-subsidence toe showed the same position as pre-subsidence toe.

A site inspection was made during a low-tide, which showed two displaced dwarf walls on the slipped bank. Originally these were (respectively) at the top

edge of the bank and at the bank slope at the low water level (LWL). Enquiries made from local elderly persons indicated that during the 1942 cyclone, the high bank was washed away. After the cyclone, the high bank was built up, which covered a good part of the low areas (below the LWL), because there was much demand of the high land for transport facilities. Above the LWL the sloped bank was lined with brick lining to stand against wave-wash. However the lower part of the filling could not be consolidated, being under LWL all the time.

The crossing of the perpendicular-bisectors of each of the two lines joining the pre-subsidence and post-subsidence positions of the respective two dwarf-walls, indicated the centre of the possible slip-circle. A circle was drawn (on the cross-section) with radius up to the exposed slipped surface of the bank. The lower end of the circle crossing the sloping bank showed the limit of the slipped soil mass. This tallied with the physical conditions, as were seen on the sloping bank. The lower part (about one-third) of the slope had not been disturbed; the toe area was also not disturbed.

The estimated shear stress along the slip-line (slip-circle line) was found to be much more than the shear strength expected from the filled up material, (considering even about only two-thirds of the godown heights being filled up with cement, etc.).

Thus it was concluded that the subsidence (in the upper part) was caused by slip-circle failure in the unconsolidated soil filling from below the LWL, which prevented consolidation. The undisturbed lower part of the foundation apparently remained intact, obviously being made up of comparatively hard soil.

Collapse of bridge across Tolly's nullah near Kudghat

At the request of the Government, Chakravarty took up the investigation of the cause of the collapse, which took place in 1989. It was understood that the bridge was designed and constructed by a firm under a turn-key contract. Although the girders were used as parapets, it was not a parapet-girder bridge according to text-books, in view of the fact that the two girders were independent of the decking and not anchored to the same. The two girders were of pre-stressed R.C. design, while the deck slabs were precast and placed on the ledges projecting on the inner side of the lower booms of the two girders. Obviously, to minimise the tender value, the firm eliminated the inner flanges on the upper booms of the two girders, so that the girders could be brought nearer, keeping the specified clear

road-width. The pre-stressing steel bars being within the thin vertical web of the girders, the compressive loads produced in the upper booms (due to pre-stressing) were concentric to the upper booms. Under the circumstances, there would be more compression on the inner side than on the outer sides of the upper flanges, and this would tend to produce a curvature in the upper booms.

An inspection was made at the site of the bridge, which showed that the southern girder had been thrown off the abutments, while the norther girder was in position. All the deck slabs had dropped into the river. The upper boom of the northern girder was found to have a bend outwards as expected, due to eccentric pre-stressing.

Enquiries made from the local people indicated that at the time of collapse, some people had gathered over the bridge (near southern girder) to see a dead body in the river. The number of persons might have been 60 or so. In any case the loading was much smaller than designed load for the bridge. It was thus obvious that the collapse was due to compressive load caused by the additional bending moment (due to the crowd-load) which acted upon the upper boom (of the southern girder) already bent due to the eccentric (prestressing) compressive load. The boom was not designed for taking the compression in the bent position.

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Dipankar Chakravorty

The work of Chakravorty has been concerned mainly with glasses, ceramics and nanocrystalline materials.

Memory switching behaviour has been observed in certain oxide glasses containing dispersed metal particles of nanometer dimension. A theoretical model has been proposed to explain the effect on the basis of particle-stretching consequent to the application of an electric field.

Chakravorty has shown that semiconducting behaviour in oxide glasses can also arise due to the presence of antimony and arsenic, each of which has both trivalent and pentavalent states. Detailed investigation on melt quench as well as sol-gel derived glasses has led to the conclusion that overlapping large polaron tunnelling mechanism is operative in these systems.

A glass fibre drawing process has been developed by Chakravorty, in which the conventional bushings made of platinum-rhodium alloy have been replaced by ceramic ones (either pure alumina or stabilised zirconia). Electrically conducting fibres having a microstructure consisting of metallic granules of nanometer dimensions dispersed within the matrix have been prepared.

Nanocrystalline metals of different species have been synthesized within a silica glass matrix by the sol-gel technique. Optical absorption characteristics have been explained on the basis of effective medium theories. Nanosized metal particles have also been prepared by subjecting suitably chosen glass-ceramics to an ion exchange process, followed by reduction treatment. The resistivity change as a function of temperature has been explained on the basis of fractal dimension of the metal aggregates. The synthesis of nanocrystalline metal by an electrodeposition method carried out in a glass medium has been introduced. The fractal growth of metal nanoclusters has been delineated.

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Some novel characteristics of the glass-metal nanocomposites synthesized by Chakravorty and co-workers are : high dielectric permittivity indicating the possible experimental confirmation of Gorkov-Eliashberg anomaly; a metal to semiconductor transition, which appears to arise due to a quantum size effect; superparamagnetic behaviour of iron nanoparticles.

Nanocrystalline PbS has been grown in a polymer medium. Electrical properties of these composites show a rather large increase in the band gap, as compared to that in the bulk counterpart.

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Biswa Nath Das

Das has a strong background of electromagnetics and solved problems of engineering interest in this field. His work has been concerned with solution of problems of microwave networks, transmission lines and antennas for microwave frequency band.

Antenna synthesis

Das made formulation for finding the aperture distribution of array which gives maximum directivity. The method is based on transforming an array into equivalent array, in which the pattern functions satisfy orthogonality conditions. The effect of random fluctuations of excitation function of array elements on the gain and directivity has also been evaluated.

Slot antenna and arrays

Derived formals for equivalent network parameters of slot radiators of arbitrary length in the broadwall of a rectangular waveguide for longitudinal as well as transverse orientations, using variational formulation in the spatial as well as spectral domain. The formula for the conductance of inclined slot in the narrow wall of a rectangular waveguide using spectral domain formulation has been found to be very accurate.

Method of optimum design of long slot array has been worked out. Emphasis has been paid to maintain more or less constant input VSWR and insertion loss over a large frequency band.

Analysis has also been carried out to determine equivalent network parameter of strip/microstrip line fed slots by Das.

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Slot coupled junctions

Array of inclined slots in the narrow wall of rectangular waveguide produces undesired cross-polarised radiation. A new type of slot coupled junction designated coplanar *E-H* plane T-junction has been analysed, designed and fabricated. When array of inclined slots in the narrow wall of waveguide excite these junctions, they produce radiation only in one polarisation, with complete suppression of cross-polarised radiation. Analysis has been carried out using variational as well as moment method formulation by Das.

In addition, analysis, design and fabrication has been carried out for slot-coupled *H*-plane T-junction between rectangular to rectangular and rectangular to circular waveguide using variational as well as moment method. Elements of the scattering matrix of the junction in terms of geometrical parameters of the junction have been obtained. There has been excellent agreement between theoretical and experimental results. Analysis has been carried out for long aperture slot couplers.

Formulas for coupling of slot couplers between strip/microstrip line to waveguide have been derived using rigorous formulation by Das.

Phased array and microwave components for phased array

Das made useful contribution for the hardware development of phased array system. Certain grid configuration of phased arrays result in a saving in the number of elements for a particular performance requirement. This ultimately results in a reduction in overall cost of phased array. An analytical expression which permits estimation of the number of elements for any grid configuration of array antennas has been derived.

The only method of making a phased array acquire multifunction capability is to change the beam shape using phase only control, and scanning of the shaped beam. Analytical expression which gives the dependence of phase distribution on radiation pattern and scanned position of the beam has been derived.

Phased arrays for microwave frequency band use open-ended waveguide as radiating elements. These are excited through coaxial lines. Since the waveguide radiators have to be very closely spaced to avoid generation of grating lobes, the system requires use of a very special type of coaxial line to waveguide transition, called end-launcher type of coaxial line to waveguide transition.

Analysis has been carried out by Das to derive design formulas for such transitions from coaxial line to rectangular as well as circular waveguides. Design of phased array for mobile communication through satellites has been worked out.

Application of conformal transformation

A general conformal transformation has been developed for analysis of strip line, in which the strip is asymmetrically located between ground planes. Expressions for equipotential, flux line and field distribution have been derived in terms of inverse elliptic functions of 1st and 3rd kind.

From this generalised formulation, formulas for impedance and field distribution have been derived for symmetric location of the strip and also for microstrip line both in presence and absence of dielectric.

The method has been extended to the cases of nonplanar strip line, i.e. for grounded cylinders with arc strip. The cases of circular as well as elliptic contours have also been covered.

Appropriate conformal transformation has been developed for the case of the central conductor having a nonplanar boundary and located between planar ground planes. General formulas for an oval shaped conductor arbitrarily located between ground planes have been derived. The general formulation has been extended to all possible special cases.

Green's function formulation

Green's function has been derived for strip/microstrip and rectangular coaxial and has been used for finding impedance and field distribution.

Multiconductor line and time domain formulation

There has been considerable attention on cross-talk in multiconductor line in a cable run. Some complicated problems on dielectric coating in these lines have been solved. A simplified approach on solving time domain response of multiconductor lines excited by a transient type of current pulse has been developed.

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Jajneswar Das

The major interest of Das in communication theory and systems was reflected in his early work on pulse slope modulation—a new TDM system (1952-60)[1,2]. His interest in signal approximations and digital communication led to the development of a highly efficient digital communication system called adaptive delta modulation. Over the years (1952-82), he has built up a School of Study and Research in Digital Communication Systems and Bandwidth Compression Techniques at IIT Kharagpur. He has also guided research on active filters and data communication. He has guided PhD theses in the areas of network approximation and synthesis, bandwidth compression, asynchronous pulse modulation systems, PCM and ADM, incoherent-carrier communication system, coherent and wideband communication systems, and random access communication systems.

As a result of the studies on the various aspects of digital communication as noted above, the following digital subsystems were developed over the years, viz.

(a) PCM Codec[3]

(b) ADM Codec[4-7]

(i) Binary (ii) Ternary and (iii) 6/12/24 channel MUX System.

(c) Low-bit-rate codecs[8]

(d) Modems[9]

The ADM MUX system suitable for VHF/UHF communication links was being manufactured by a public sector industry for mobile and area-grid communication.

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Along with the above work on synchronous digital systems, investigation on asynchronous digital systems led to the development of rectangular wave modulation[10] and pulse interval modulation. These were intended for simple communication systems and were later on incorporated in random access systems for mobile communication[11]. The problem of incoherency of carriers using solid-state lasers was solved by developing optimum modulation techniques and this resulted in a novel method of eliminating fading effects in scatter communication[12].

Das has been associated with Defence R and D for a number of years (1965-82). He and his group were responsible for carrying out a number of projects on digital communication and allied topics, sponsored by DRDO and also by ISRO.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Bulusu Lakshmana Deekshatulu

Deekshatulu's research work spans over 3 decades (since 1960) with more academically oriented research work in control systems in the first 15 years and later developmental and research work in digital image processing; both at Indian Institute of Science; and later operationalisation and promotion of remote sensing since 1976 at the National Remote Sensing Agency, Hyderabad. Deekshatulu has distinguished himself as a visionary who had the foresight to introduce two very important contemporary technologies into the country, when they were in their developmental stages even in advanced nations.

(a) In the first half of his career as a scholar, researcher and teacher, he was instrumental in the introduction of control systems into the undergraduate and post graduate engineering classrooms besides research. Research work carried out by him and his students in control systems engineering has led to the establishment of School of Automation at the Indian Institute of Science in 1972. (b) Subsequently his interests were in digital image processing, pattern recognition and computer techniques leading him towards remote sensing.

Deekshatulu has succeeded in creating the necessary infra and supra structural facilities besides introducing teaching and research in the above areas, with the result that strong schools of research are headed by his students in control and image processing areas at Indian Institute of Science and he himself heads the National Remote Sensing Agency which has grown both qualitatively and quantitatively since 1976.

In the area of non-linear control systems, his contributions have been in phase-plane analysis and describing function and in different types of linear/non-linear systems analysis.

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Non-linear control systems

The describing function (DF) for a nonlinear element is evaluated from the nonlinear characteristic without going to the output waveform and is shown to be a fraction of a certain area obtained by a simple graphical construction. The method is applicable to all nonlinearities. Phase shift, if any, is also determined in terms of areas. Other methods of evaluating DF include approximating output waveform by straight line segments, taking ratio of the total area in one period of the output waveform to that corresponding to the input waveform, describing function for successive non-linear elements, etc.

By approximating phase-plane (x—x) trajectories by straight line segments, time solution of second order nonlinear differential equations is obtained easily step-by-step. Analysis of certain second order and higher order nonlinear systems, not easily amenable to the phase-plane methods, using generalised phase planes such as $\dot{x}^n$-$\dot{x}$, $R = (\dot{x}^2 + \dot{x}^2) - x$ or x, $tx - x$, $t\dot{x}^2 - x$, etc., are considered novel and significant. Time evaluation is done again using straight line approximation to the trajectories.

By considering simultaneously the two plans $\dot{x}$—x and $\dot{x}$—x the isocline method is extended to find (for all initial conditions) the behaviour of second-order nonlinear autonomous systems which are not easily amenable to the usual phase-plane methods. The effect of variation of nonlinear functions can easily be studied. Simple as it is, the method is believed to be novel. Developed a novel method of obtaining the entire phase-portrait by the phase-plane delta method and also constant time loci in the phase plane for nonlinear systems. Methods have been suggested for analysis of second order (a) time delay system, (b) time varying systems and demodulation type compensating networks. A method is given for process identification and adaptation by high frequency sinusoidal test signal. Other research in control systems include, effect of intermittent regulation on power system steady state stability, performance evaluation of optimal linear systems, asymptotic method of Krylov-Bogoliubov to over damped non-linear systems, sensitivity analysis of optimal linear systems, etc.

Image processing

In image processing, Deekshatulu established a laboratory for IP at the Indian Institute of Science and got fabricated the first drum scanner in India. It may be pointed out that the scanner has now been refined at NRSA and is being marketed

by an Indian company. It is a replacement for an imported system costing about Rs 1 crore. Through his students, his research work in IP is in the area of character recognition, biomedical image analysis and stochastic method for optimization.

Remote sensing

During the early seventees, remote sensing technology was just coming out into civilian use at the initiative of the "Open Sky Policy" of the United States. Deekshatulu was involved in establishing remote sensing facilities at Indian Institute of Science for aerial data acquisition, using modified Pushpak aircraft housing multispectral cameras and the subsequent processing and analysis. Since 1976 at NRSA he has set up facilities for satellite data reception, interpretation and data dissemination and succeeded in making NRSA a premier national institution of international repute.

Deekshatulu has contributed significantly towards conceptualisation and development of applications and several of these applications in landuse, agriculture and soils, forestry, geosciences, hydrology, water resources, etc., which are now being operationally carried out all over the country.

Deekshatulu was involved in the formulation of the end-to-end satellite remote sensing application programme, which has successfully culminated in the development, and operationalisation/utilisation of IRS-1A and 1B satellites which has put India amongst the top 5 countries in the world with such a capability. Policy initiatives at high levels of the Government, promotional efforts amongst the users, education/training programmes for user scientists are the areas in which Deekshatulu spearheaded the nation's programmes.

The National Natural Resources Management System (NNRMS) in India is a model which is the envy of many countries in the world and Deekshatulu was instrumental in ensuring the smooth execution of many operational (connected with NNRMS) Centres/Institutions such as RRSSCs, NRSA/SAC, State Remote Sensing Centres, national laboratories, etc. Simultaneously, he has led several teams for development of remote sensing data interpretation and analysis instruments involving optics, electronics and precision mechanism and these have been successfully productionised through technology transfer to industries. Examples are: Drum Scanner Digitiser, Photo Write System, Image Analyser,

Multispectral Additive Colour Viewer, PC-based Image Analysis System, Densitometer, etc.

The introduction of remote sensing technology in an operational mode has used a multiplier effect in the application of the visible, infrared and microwave remote sensing technology on a very large scale all over the country. The awareness among the resource managers regarding use of remote sensing data for district planning and development and environmental issues has increased as a result of these efforts. Information obtained from remote sensing has become a strategic business information system.

Deekshatulu's initiative and execution in applying remote sensing for ocean related applications is bearing fruits in identification of potential fishing zones and in analysing other sea related parameters. Also use of artificial intelligence (AI), neural networks and fractals in data interpretation, use of microwave data and geographic information system (GIS) development at NRSA are going to bring rich rewards in the years to come.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Dinesh Mohan

Dinesh Mohan's active research career began in January 1948 when he joined the Central Building Research Institute (CBRI), Roorkee as a Senior Scientific Officer. Soon after he was designated as its Planning Officer and took over as Director in October 1962. He held this post for two decades till his retirement in July 1982.

Apart from planning the CBRI in all aspects, including buildings, staffing and equipment in its formative stage, Dinesh Mohan held charge of the Geotechnical Engineering Division for 10 years (1950-60). During this period, he organized and conducted research on a number of important projects in geotechnical engineering. His major achievements are discussed below in brief.

Black cotton soils

Almost 20% of the total land area in India consists of black cotton soils, concentrated mostly in Central India (Madhya Pradesh). These are heavy clays with montmorillonite as the predominant clay mineral due to which the soils have high shrinkage and swelling property. This property makes them problem soils for the foundation engineer. Prior to 1950, cracking of buildings founded on black soils was taken as an 'act of God'. Dinesh Mohan carried out some basic studies on the properties of these black soils, which finally led to the design and development of bored underreamed pile foundations. Apart from testing the physico-chemical properties and correlating them with engineering properties, such as compressibility, shear strength, bearing capacity etc., a two-year field study was carried out on ground movements at various depths starting from the surface down to 4 m. The study revealed that movements were negligible at a depth of about 3 m; this gave a clue to the depth at which the foundations could be anchored safely. The tip of the pile was enlarged in the form of a bulb, to 2.5

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times the diameter of the stem, to act as an anchor and also to provide a greater bearing area. A simple and manually operated underreaming tool was developed for this purpose. Full size piles were load tested and their bearing capacities determined in loading and pull out. These were correlated with the engineering properties of the soil and a rational design was thus formulated. Further improvement of the technique led to the development of multi-underreamed piles which had more than one bulb on the lower portion of the pile. Each extra bulb could carry 50% greater load. These piles could thus carry heavier loads and they proved economical as compared to large and uniform diameter bored piles being used so far.

A further improvement was made in the form of bored compaction piles. These were either uniform diameter or single underreamed piles in which concrete, still in the green stage, was compacted by ramming a close ended steel tube through it. It ensured better compaction of the concrete as also strengthening of the ground adjacent to the piles. These piles have 50-100% greater load carrying capacity compared to the normal bored piles, and are specially suited for soft to medium dense soils ($N < 15$). An Indian Standard Code of Practice has been brought out to help the design and construction engineer. These foundations need simple and light equipment and are 25-50% cheaper than the traditional strip or pile foundations. A large number of buildings of all type—tower, hydraulic structures, etc. —have been constructed on these foundations and from all quarters satisfactory reports regarding their subsequent behaviour and substantial economy achieved have been obtained.

Pile foundations

Pile foundations are generally required for heavy structures founded on poor soils like those existing in Bombay and Calcutta. These are required even for normal soils carrying tall structures and high rise buildings. Prior to 1950, pile foundations were being designed and executed by a few foreign owned piling firms. The design was mostly empirical and was based on experience. Most of the pile foundations were therefore, overdesigned and the clients accepted them, since no simple guidelines were available to them to check designs.

Dinesh Mohan carried out detailed investigations on all aspects of pile foundations. These studies led to the formulation of a number of Indian Standards

and Codes of Practice on different types of pile foundations. His studies and those carried out elsewhere are incorporated in Ref. 1.

Site investigation and subsoil explorations

Site investigations are a very important part of any major foundation project. Faulty or casual site investigation and soil testing has led to many foundation failures necessitating costly remedial measures.

A careful study was made of the existing techniques of site investigations, and new and simple techniques were developed. One example is the dynamic cone penetration test, which can replace the internationally accepted standard penetration test. The latter is laborious and time-consuming. Another example is the one-point method of liquid limit test, which simplifies and speeds up the most common soil test to determine the consistency of a soil.

Primary school buildings for rural areas

There is great shortage of primary schools in the country and the shortage has been further aggravated by the national objective of providing free and compulsory primary education to all children. The conventional designs and methods of construction of primary schools are costly and time-consuming.

The Central Building Research Institute, under Dinesh Mohan's direction, carried out a scientific study of the use efficiency of spaces in the conventional type primary schools of Uttar Pradesh. It led to an improved design giving considerable saving in space and cost of construction. Further economy and speed in construction were achieved by the use of prefabricated roofing components and local materials and labour. A very large demonstration project covering 2500 primary schools in rural areas of Uttar Pradesh was carried out by CBRI during 1977-79. In the first stage, each school had two classrooms and a small store; it could be later expanded into five classrooms and a headmaster's room. The design led to a saving of about 20% in cost and 50% in time of construction over the traditional types. It also provided employment opportunities for about 2.3 million man-days, of which about 0.67 million man-days were for skilled workers and about 1.6 million man-days for unskilled village labour. The prefabricated roofing units and other components were developed as a consequence of the research carried out at the CBRI.

Health care building in rural areas

With the stress on better health care for the rural areas, the World Bank financed a major project for the construction of primary health centres, subcentres, family planning centres and allied buildings in rural areas of Uttar Pradesh. CBRI was called upon to act as the Chief Consulting Architect for the design of these buildings.

Under Dinesh Mohan's direction, CBRI had carried out extensive studies in the functional design of health care buildings in rural areas. These studies came in very handy for the design of the World Bank project. Considerable economy in space was achieved through judicious planning. Prefabricated roofing components were used to further economize in cost and time of construction.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Dwijesh Kumar Dutta-Majumder

Dutta Majumder started his professional and research carrier with the only first generation digital computer system in India in ISI in late fifties and currently involved with R & D problems of fifth generation computing systems. He has made substantial contributions in different areas of computer science in both theoretical and experimental aspects including applications. He started with computers' memory technology and then switched over to its problems of cognition and contributed immensely in the areas of pattern, speech and image processing and recognition, artificial intelligence, computer vision, cybernetics and systems theory, fuzzy mathematics and applications, human computer interfacing, computer communication problems, and knowledge based computing systems development.

Computers' memory technology

Dutta Majumder designed, developed and fabricated in early sixties several state-of-the-art magnetic drum and core memory[1] systems which could be used in computers making the country self-sufficient. He along with his student and colleague J Das wrote a classic book on Digital computers' memory technology[2] covering all aspects of computer memory.

Speech and music research

From computers memory he switched over to its problems of recognition and started with speech patterns. He conducted extensive acoustic, phonetic and spectrographic investigation of speech sounds of three major Indian languages Bengali, Hindi and Telugu and developed automatic speech recognition and speaker identification systems[3] along with the theoretical tools of statistical and fuzzy set theoretic approaches. He was the first to apply fuzzy set theory in speech and other pattern recognition problems. He also made some significant contributions on spectrographic computerised studies of north Indian classical

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music in collaboration with Sangeet Research Academy. Speech and music research group of ECSU, ISI established and developed by him is a leading centre of research in the country.

Fuzzy mathematics and applications

Dutta Majumder proposed a new fuzzy mathematical approach to solving pattern recognition problems and made extensive contribution using this approach in speech recognition, speaker identification, picture processing[4,5] and logic controller design problems. Fuzzy Mathematics and Applications Group at ISI established and developed by him is known throughout the world for its high quality research.

Cybernetics and systems

In 1977 Dutta Majumder wrote a seminal paper entitled *Cybernetics and general systems' theory — a unitary science*[6]. He along with one of his colleagues extensively worked[7] on fuzzy logic controller design in relation to nonlinear steam generating unit. Currently he is engaged in applying his unified theory of cybernetics and systems to problems of cognitive science, psychodynamic and mind-body problems.

Pattern recognition computer vision and man-machine communication problem

As mentioned earlier, in late sixties Dutta Majumder switched his interest from computers' memory to its cognition, but main motivation was to develop man-machine communication in natural mode, namely speech and vision. After extensive investigation on speech pattern processing[3,4] in human and machine, he initiated research in visual pattern recognition, image processing and computer vision. Dutta Majumder made seminal contribution on image enhancement, restoration, clustering, recognition, and description of 2-D and 3-D shape/scene analysis with and without occlusions, date compressions, parameter learning, fractal-based criterion for image magnification, connectionist (neural) and several models for image pre-processing and object recognition, and minimal spanning tree (mst) approach to cluster analysis. Dutta Majumder while developing PR techniques for speech, visual and other patterns used fuzzy/statistical/syntactic mathematical approaches with parametric/non-parametric and supervised/ unsupervised models and applied them to real-life problems[8].

Dutta Majumder as principal investigator applied these theories and mathematical tools in following large scale projects of national importance in collaboration with respective users with published technical reports:

1. Development of a continuous non-fading patient monitoring system (DoE).
2. Statistical study of tropospheric propagation for UHF and microwave links in eastern India (DST).
3. Development of pattern recognition techniques for geological resources mapping from satellite imagery and mineral identification from microphotographs (DoE and GSI).
4. Development of pattern recognition and shape analysis and target identification techniques from satellite imagery for military applications (DRDO) and similar work for Natural Resources Study and Estimation.
5. Development of on-line inspection system using pattern recognition and image processing for (a) cold-rolling mills, (b) coal quality analysis, (c) ferrogram analysis, (d) water quality analysis, (e) bio-medical diagnostic applications, etc. (NCKBCS-DoE/UNDP programme).

FGCS/KBCS developments and applications

In early eighties with the Japanese announcement of fifth-generation computer systems (FGCS) development project, Dutta Majumder took a key-role in starting an Indian initiative through large number of lectures/papers resulting in DoE/UNDP sponsored FGCS/KBCS multi-institutional project in 1986 with himself as one of the national co-ordinators. In this connection he built up the National Centre for Knowledge Based Computing at ISI, which is a centre of excellence in the country. On the basis of his earlier work he developed a unified approach to pattern recognition, image processing, computer vision and artificial intelligence [12,13] and developed some real life cost effective PC-based inspection systems for coal quality analysis, rolling steel inspection, ferrogram analysis, water quality analysis, boiler tube leakage detection, biomedical diagnostics and breast cancer screening. He also developed some methodologies for analyzing satellite based remotely sensed imageries and applied them for mineral location targeting, military target identification, natural resource study and urban planning.

Computer Communication and related lower atmospheric studies

Dutta Majumders' primary concern was to take India at the international level in different aspects of computer technology and to develop their applications in Indian context. In mid-seventies he carried out a thorough analysis of infrastructural requirements for computer communication networking in south

Asian countries and presented at SEARCC-76 at Singapore, in which he showed that satellite communication will be cheaper, but lower atmosphere needs to be studied thoroughly. His technical reports of DST sponsored project on statistical study of tropospheric propagation for UHF and microwave links in India, along with some publications and technical reports on atmospheric boundary layer studies using SODAR and other remote sensing technologies are significant from that point of view. He has also established an R & D group which is engaged in pioneering work of applying pattern recognition, image processing and related computerised techniques in the study of lower atmosphere including pollution problems.

Dutta Majumder has also initiated development of some cost effective PC-based pollution inspection systems for quick quantitative analysis of water, air and soil pollution in collaboration with pollution control agencies in Calcutta.

Knowledge-based approach to bio-medical problems

Dutta Majumder and his colleagues have developed a PC-based breast cancer self-screening expert system in collaboration with cancer experts, which has been marketed by a Calcutta based software company in India and Germany. He is currently working on a scheme to apply some of his ideas in relation to 3-D bio-medical images, such as emission computed tomography (ECT), magnetic resonance imaging (MRI), signal photon emission computed tomography (SPECT), and positron emission tomography (PET) and to represent them in an expert system framework for visualisation in a combined way or separately for diagnostic purposes by the medical community[14]. The envisaged system and most of the algorithms have already been developed; this will be a cost effective PC-based one.

Artificial intelligence, cybernetics and mind-body problem

Dutta Majumder is trying to develop a unified framework of artificial intelligence, cybernetics and the controversial mind-body problem. The subject[15] is at the intersection of physics, philosophy, physiology, psychology and computer science.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Suhash Chandra Dutta Roy

For more than three decades, Dutta Roy has been involved in some exciting research problems on circuits, filters and signal processors using various kinds of devices, viz. lumped and distributed, passive and active, and analog and digital. The main goal of his efforts has been to make them efficient, reliable, economic and compatible with the demands of fast changing technology. The present account highlights the results which are considered as important advances.

Lumped networks

Dutta Roy investigated various kinds of frequency selective *RC* networks, viz. the Wien, parallel-T, bridged-T, bridged ladder and shunted ladder[1], and evolved new design and tuning procedures. He obtained concise mathematical formulas for a general ladder network and applied them to the design of *RC* phase shift oscillators, and to the problem of potential distribution across a string of insulators, as encountered in power distribution. For *RC* ladders, he derived closed form expressions for the delay and rise times. He found general solutions for the insertion network required to maintain constant voltage or current in a varying load.

Passive network synthesis and filter design

Minimal realizations of nonminimum phase biquadratic *RC* transfer functions; equal valued, common terminal capacitor synthesis of *RC* one ports; and synthesis of optimal passive integrators are some of his interesting contributions to passive network synthesis.

Dutta Roy showed that practical dissipative reactors can be used in constant resistance filters. He investigated, in detail, sharp cut-off filters[2] obtained by introducing transmission zeros in the stopband, and gave simplified design procedures for them. A new family of transitional Butterworth-Chebyshev filters;

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a simple method for obtaining arithmetic symmetry in bandpass filters (BPF's); and a minimum phase low pass filter (LPF) with flat delay and equi-ripple magnitude, are some of his other contributions to filter design.

Dutta Roy worked out a method for reducing overshoot and ringing in the step response of conventional filters, and provided a definite answer to the outstanding question concerning the optimum pole locations of filters for pulse applications.

Distributed networks

The distributed *RC* network (DRCN) is an important byproduct of IC technology. Dutta Roy worked on the theory of uniform (U) as well as nonuniform (NU) DRCN's, and their applications in phase shift oscillators[3], notch filters[1] and wideband delay lines.

The NU transmission line (NUTL), of which the NUDRCN is an example, is governed by a differential equation, which is not, in general, exactly solvable. Dutta Roy developed systematic procedures for finding solvable NUTL's and a simple method for finding their two-port parameters. Even for a solvable NUTL, analysis and synthesis problems are quite involved because of the transcendental nature of the network functions. Dutta Roy developed simplified rational models for obviating this difficulty.

Dutta Roy carried out extensive investigations on an impedance matching network using lossless TL's, originally suggested by Ruthroff. Dutta Roy found that using a NUTL, one can increase the matching bandwidth drastically, and that the Ruthroff connection applied to a cascade of two appropriate UTL's leads to frequency independent or all-pass matching[4]. His other contributions in lossless TL's include a general result on coupled NUTL directional couplers; a new NUTL for voltage pulse compression; and general formulas for cascaded commensurate UTL networks.

Dutta Roy found a useful application of the DRCN concept in modelling solid state devices. For example, he showed that the transistor current amplification factor alpha could be exactly represented by a capacitor terminated exponential NUDRCN. Another application of the DRCN which he pursued[5] to great depths is in network approximations of the irrational function s^{λ}, $0<\lambda<1$. Recently he has worked out excellent lumped approximations of $s^{1/2}$, $(s+1)^{1/2}$ and $(s^2+1)^{1/2}$, by using a flexible continued fraction expansion technique.

Inductance (L) simulation, active RC synthesis and filter design

At low frequencies and in integrated circuits (IC's), inductors have to be avoided or simulated. Dutta Roy's early work on L-simulation was based on properties of semiconductor devices, but their excessive temperature sensitivity made him look for alternative philosophies. The high quality integrated operational amplifiers (OA's) provided the answer and he succeeded in simulating temperature and OA parameter insensitive grounded as well as floating L's. Various circuits were proposed by him, including one for ideal L, and critically studied[6]. In the case of floating L's, his solutions are economic and avoid critical adjustment problem usual with other known circuits. He applied the simulated L's to the direct as well as the cascade form active filter design and derived a number of new, versatile, economic and low sensitivity second order blocks.

Dutta Roy's other contributions to active RC synthesis and filter design include single OA all-pass circuits; active RC synthesis of driving point functions; a single OA multifunction second order structure; equal, grounded C realization of all-pole transfer function; and a novel technique for calculating the sensitivity of third and higher order filters.

Digital signal processing (DSP) and filtering

Most of Dutta Roy's recent research has been concentrated in this very dynamic and active field, and his early efforts were concerned with digital filter design starting from known analog filters. Later, he developed a computationally efficient matrix formulation of the discrete Hilbert transform (DHT), and applied it successfully to the design of a digital LPF.

Finite word length effects, resulting in coefficient quantization and multiplication roundoff errors, were extensively studied by Dutta Roy. His contributions include relation of architecture to quantization errors in second order digital notch filters; new, efficient methods for evaluating multiplication roundoff errors; application of pseudo-Boolean technique to FIR[7] and IIR designs for minimization of coefficient quantization errors; a new "nested" structure from FIR filters, which achieves, with fixed point implantation, the same accuracy as that of floating point[8]; and new low sensitivity recursive structures for all kinds of filters.

Single parameter controlled variable digital filters, as required in speech processing and spectrum analysis, using a first order (1°) all-pass transformation on an IIR prototype gives rise to delay free loops; Dutta Roy devised a simple computational trick to avoid this problem. For an FIR prototype, he evolved an

efficient 2° cosine transformation which obviates the limitations of the unusual 1° case. He also derived efficient methods for designing BPF's with fixed centre frequency and variable bandwidth or vice versa.

Dutta Roy evolved a new and general method for frequency domain interpolation[9], in which the order of computation is retained at the FFT levels, and gave an efficient solution to the problem of time domain interpolation by using low order differentiators[10]. An exclusive time domain solution has been proposed by him for estimating the frequency of a single sinusoid embedded in broadband noise, using iterated auto-correlation technique.

Dutta Roy worked extensively on digital filtering using identical blocks, initially concerned with sharpening the response, and later extended to frequency transformation and variable filtering.

Recent notable work of Dutta Roy on DSP includes explicit analytical technique for the design of maximally flat FIR filters with specified cutoff frequency; a new design of maximally flat and monotonic FIR filters by using the Bernstein polynomials[11]; design of narrowband digital differentiators based on maximal linearity, rather than the usual minimax error criterion, its extension to higher order differentiators[12], and a novel, universal architecture[13] for such differentiators, which can be frozen into an IC chip; interrelationships amongst digital differentiators, Hilbert transformers and half-band low-pass filters; simple methods of phase and delay interpolation; and efficient methods of computation of univariate and bivariate polynomials[14] at equally spaced intervals.

Charge transfer device and its applications in signal processing

The charge transfer device (CTD) is uniquely suitable for many signal processing situations, but its applications have so far been limited due to its charge transfer inefficiency (CTI). Dutta Roy investigated a number of techniques for CTI compensation, and developed a new one, based on feedback, which could give exact compensation of an N-stage CTD with N feedbacks. He also showed that only two feedbacks are adequate for practical purposes, and using this concept, he evolved a simple and accurate method for measuring the CTI.

Dutta Roy showed that the coefficient sensitivity in a CTD transversal filter could be drastically reduced by implementing it with difference coefficients, and evolved a new concept for economic implementation of the prime transform algorithm in a CTD transversal filter.

Work in other fields

Besides the fields elaborated so far, Dutta Roy has worked on a few interesting problems in measurements and instrumentation, electronic circuits and antenna arrays. Of these, single shunt fault diagnosis in a resistive ladder, single resistance controlled *RC* oscilllators[15], and design of four element nonuniformly spaced antenna array, deserve special mention.

Future directions

Dutta Roy plans to concentrate his research efforts in the field of DSP, with a view to developing direct and analytic design procedures, which are not extensions of their analog counterparts, and which minimize dependence on computer optimization. What he has achieved so far is considered by him as only partial success; much more needs to be done to establish this field on the same firm and analytic grounds as analog signal processing and filtering.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Ramachandra Janardan Garde

Garde has a strong background in fluvial hydraulics, fluid mechanics, and hydrology and has made significant contributions in all these branches.

Fluvial hydraulics

On the basis of analysis of a large volume of data from laboratory flumes and alluvial rivers, Garde has studied the characteristics of various bed-forms occurring in natural streams viz., plane-bed without motion, ripples and dunes, transition and antidunes. Two regime criteria proposed by him and Albertson, and by him and Ranga Raju using dimensionless shear $\tau_o/\Delta\gamma_s d$ and Froude number $U/\sqrt{gR}$ and, R/d and $S/(\Delta\gamma_s/\gamma_f)$ give accurate prediction of regimes and are widely used[1].

Prediction of average velocity of flow in a stream for known depth, slope, and the sediment characteristics is important in solving all practical problems of alluvial streams. A method proposed[2] by Garde using R/d, $S/(\Delta\gamma_s/\gamma_f)$ and $U/\sqrt{(\Delta\gamma_s R/\rho_f)}$ as three parameters provides a direct solution for U and hence the discharge Q.

An alluvial stream carries sediment load along with the flow and its correct evaluation for known hydraulic conditions is important in the solution of problems related to the stability of rivers, reservoir sedimentation, aggradation and degradation, etc. Depending on the flow conditions and sediment size the transported material can move as bed-load or as bed-load and in suspension. Similarly, the material in the river bed is always nonuniform; hence there are effects of greater exposure of coarser particles to flow and smaller particles are shielded. All these aspects of sediment transport have been analysed in various papers and working relations obtained[3-5].

For carrying water from barrages to irrigated fields, canals have to be dug through noncohesive material. The dimensions and slope of such unlined stable

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channels have to be such that they carry given amount of water and sediment discharge through the canal without appreciable deposition or scour and their banks are stable. A method has been developed based on dimensional reasoning[6] which makes use of all the available data from India and abroad.

Other aspects of fluvial hydraulics such as the bed material characteristics[7], velocity of bed forms, flow and scour in bends, physical modelling of alluvial streams, longitudinal profile of river and criteria for the deposition of sediment have also been studied.

Scour

One of the important problems in fluvial hydraulics is the scour around hydraulic structures, such as bridge piers and spurs. Garde has investigated systematically the effect of various parameters such as pier size, pier shape, opening ratio, sediment size its nonuniformity and stratification, flow and its unsteadiness on the variation of scour depth[8,9]. A numerical modelling scheme for predicting the time variation of scour has also been developed.

Transient flows in alluvial streams

One major area in which significant progress has been made in the case of alluvial streams is in developing methods for predicting bed level variation in the case of unsteady nonuniform flows, such as reservoir sedimentation, degradation downstream of reservoirs and aggradation caused by overloading of streams. Over a period of two decades Garde has investigated these problems experimentally and numerically and devised prediction methods for bed level variation[10]

Fluid mechanics

Various problems in fluid mechanics which find application in fluvial hydraulics and hydraulic structures have been analysed by Garde. These include direct solution for problems in pipe friction, variation of drag of a sphere rolling on a plane surface[11], initiation of motion on a hydrodynamically rough surface and subcritical flow in expansions in channels[12,13].

Hydraulic structures

In hydraulic structures, Garde has analysed the flows at intakes to avoid vortex formation and given design criterion. Similarly, design methods for subcritical expanding transitions, sediment excluders and energy dissipators for tunnel outlets into a channel have been established on the basis of extensive experimentation.

Hydrology

In hydrology the data from a large number of catchments in India have been analysed to obtain a relationship for mean annual run-off and annual run-off as a function of annual rain fall, vegetal cover and relevant parameters. Similarly data from over 45 small and large reservoirs have been analysed[14] to obtain a map showing mean annual sediment yield from the catchments. This has been found to depend on annual precipitation, drainage density, catchment slope, vegetal cover factor and (P_{max}/p). Garde has also developed a method to estimate flood of a given return period for an ungauged catchment. Lastly an equation has been obtained to predict rainfall intensity of given duration and given return period, which is valid universally except for a regional constant[15].

Garde has authored/coauthored books on fluid mechanics, swirling flows, sediment transport, and turbulent flow and is presently working on history of fluvial hydraulics, and dimensions of bed undulations.

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Chaitanyamoy Ganguly

Ganguly has made several original and outstanding research contributions for indigenisation in "plutonium metallurgy" and in plutonium, uranium (including U^{233}) and thorium bearing metallic, ceramic and dispersion type nuclear fuels for research and power reactors in India. He is working at Bhabha Atomic Research Centre (BARC) for the last 24 years and has also carried out research work at the Nuclear Research Centres of FRG, namely, Kernforschungszentrum (KfK), Karlsruhe and Kernforschungsanlage (KfA), Juelich. His areas of research in nuclear fuels include: development of fabrication flowsheets, evaluation of out-of-pile thermophysical and thermodynamic properties, in-pile testing and post irradiation examination (PIE).

Plutonium fuels laboratory at BARC

Ganguly has played a key role in setting up, starting from the scratch, glove boxes and equipment for fabrication of highly radiotoxic Pu bearing metallic and ceramic fuels and characterisation of these fuels. During his initial years (1969-73) at BARC, he successfully completed the following assignments[1]:

- fabrication of stainless steel (type 316) clad PuO_2 fuel pins for PURNIMA-I reactor core;
- fabrication of Al clad Al-Pu plate fuel elements for physics experiments in ZERLINA reactor.
- fabrication of Pu-Be neutron sources (100 mCi to 5 Ci).

X-ray diffraction studies of U-Pu-C-O and U-Pu-O systems

During Ganguly's deputation in mid 1970s to Kernforschungszentrum (KfK, Nuclear Research Centre), Karlsruhe, Ganguly developed the following two analytical techniques based on X-ray diffraction, which are used in fuel fabrication laboratory in India and abroad[2,3]:

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— quantitative evaluation of monocarbide, sesquicarbide and oxide phases in U-Pu-C-O system by an absolute method; and
— determining the extent of solid solution formation in the UO_2-PuO_2 system by regression analysis of X-ray diffraction line profile.

Development of (U, Pu)C and (U, Pu)N fuels–Fabrication of ($Pu_{0.7}$ $U_{0.3}$)C fuel for FBTR

Ganguly's most significant achievement is the development of (U, Pu)C and (U, Pu)N fuels for fast breeder reactors. Based, on his Ph.D thesis titled *Studies on preparation and sintering of (U, Pu)C, (U, Pu)N and (U, Pu) (C, N)*, Ganguly[4] had developed the powder-metallurgy route for fabrication of the hitherto untried plutonium rich ($Pu_{0.7}$ $U_{0.3}$)C and ($Pu_{0.7}$ $U_{0.3}$)N fuel pellets of controlled density, phase content and microstructure, starting from UO_2 and PuO_2 powders. Simultaneously, he evaluated the thermal conductivity, co-efficient of thermal expansion, hot hardness and indentation creep of these fuels and established the chemical compatibility of plutonium rich mixed carbide and nitride with sodium coolant and stainless steel (type 316) cladding[5,6]. Next, he had set up the carbide and nitride production laboratory in BARC with a capacity for delivering one fuel core (around 250 kg) for FBTR annually. This is one of the unique facilities in the world and has been appreciated by leading scientists and technologists from India and abroad. Indigenous manufacture of the hitherto untried ($Pu_{0.7}$ $U_{0.3}$)C fuel for the first core for FBTR under his leadership has avoided import of U^{235} and has saved Rs 25 crores in foreign exchange. FBTR is the first fast reactor in the world to use this advanced mixed carbide as driver fuel. Thereafter, he had been fabricating the subsequent cores of FBTR fuel of composition ($Pu_{0.55}$ $U_{0.45}$)C. Simultaneously, he has developed[7] ($Pu_{0.55}$ $U_{0.45}$)N alternative fuel for FBTR and ($U_{0.8}$ $Pu_{0.2}$)C and ($U_{0.8}$ $Pu_{0.2}$)N fuels for the forthcoming prototype fast breeder reactor (PFBR).

Sol-gel microsphere pelletisation (SGMP) process

Ganguly did his post doctoral research with the prestigious Humboldt Fellowship of FRG in the Nuclear Research Centre (KfA) at Juelich, where he had developed the "dust-free" sol-gel microsphere pelletisation (SGMP) process for fabrication of high density UO_2, (U, Ce)O_2 (Ce for simulating Pu), (Th, U)O_2 and (Th, Ce)O_2 fuel pellets utilising the "external gelation of thorium (EGT) and uranium (EGU)" processes[8,9]. On his return to BARC, he modified the "Ammonia internal gelation of uranium (IGU)" and extended the SGMP process for fabricating of UO_2 and highly radiotoxic (U, Pu)O_2, (U, Pu)C and (U, Pu)N fuel pellets for thermal and fast reactors. He has modified the conventional "internal/external ammonia

gelation" process for obtaining after controlled calcination either porous (for high density oxide pellets) or non-porous (for low density oxide pellets with open pore structure) oxide microspheres.

By carbothermic synthesis of hydrated oxide + carbon gel-microspheres in vacuum and flowing nitrogen Ganguly prepared free-flowing, dust-free monocarbide and mononitride microspheres respectively, of diameter 200-400 microns, which were suitable for direct pelletisation and sintering[10]. Subsequently, he made judicious combination of SGMP-low temperature ($\leq$ 1300°C) oxidative sintering (LTS) process to obtain high density UO_2 and (U, Pu)O_2 pellets conforming to PHWR fuel specifications. His combined SGMP-LTS[11] process avoids radiotoxic aerosol, minimises energy and gas consumption during sintering and is referred world wide as state-of-the art method. Fuel pins containing high density UO_2 and (U, Pu)O_2 pellets prepared by the SGMP-LTS route are undergoing irradiation testing in Madras Atomic Power Station (MAPS) and in the pressurised water Loop (PWL) of CIRUS research reactor.

Thorium based fuels

As part of thorium utilisation (India has large reserves of thorium) in pressurised heavy water reactors (PHWR), Ganguly has developed viable process flowsheets based on powder-pellet, pellet-impregnation and sol-gel microsphere pelletisation processes for fabrication of high density (Th, Pu)O_2 and (Th, U^{233})O_2 fuel pellets[12]. He is responsible for initiating irradiation testing of (Th, Pu)O_2 fuels in the pressurised water loop (PWL) of CIRUS research reactor. A six pin ThO_2-PuO_2 fuel cluster has already been irradiated to high burn up (20,000 MWD/t) and a second cluster of six pins is presently undergoing irradiation in CIRUS, PWL.

Out-of-pile thermophysical properties of nuclear fuels

Ganguly has carried out pioneering work in the evaluation of essential thermophysical properties of ceramic, alloy and cermet fuels, namely, hot indentation hardness, indentation creep, thermal conductivity and coefficient of thermal expansion. Thermal conductivity measurements were carried out by him using the laser flash method, up to 1600°C. The hot hardness and indentation creep measurements were carried out by a Vicker's diamond indenter in the range of 1s-1000s. Ganguly also established the fuel-clad and the fuel-clad-coolant chemical compatibility, particularly for the sodium cooled fast breeder reactor using SS-316 as cladding material and (U, Pu)C and (U, Pu)N as fuels. These data bank provide useful information for designing and understanding of in-pile performance of metallic, ceramic and dispersion fuels.

Al matrix plate type dispersion fuels for research reactor

In recent years, Ganguly has successfully developed the knowhow and process flowsheet for fabrication of Al clad Al-20% U^{233} and Al-23% Pu plate fuel element for the KAMINI research reactor at IGCAR, Kalpakkam, based on "melting-casting-picture-framing-roll-bonding" technique[13]. Such U^{233} bearing fuel is being used in research reactor for the first time in the world. Subsequently, he has successfully developed the process flowsheet, for fabrication of Al-Mg alloy class Al-UAl_x, Al-U_3O_8 and Al-U_3Si_2 plate fuel elements for the forthcoming multi-purpose research reactor (MPRR) of capacity 5MWt and 10MWt, for export[14]. The Al-UAl_x, Al-U_3O_8 and Al-U_3Si_2 fuel meats were prepared by "powder metallurgy" process, including mixing Al matrix powder ($<$ 44 microns) with UAl_x, U_3O_8 or U_3Si_2 dispersant (25-150 microns), cold-pelletisation (500 MPa) and sintering (500°C). Thereafter, the fuel meat is sandwiched and picture framed in Al-Mg alloy plates and roll-bonded.

Zirconia based engineering ceramics

With his experience in oxide and non-oxide fuels for nuclear reactors, Ganguly did some basic work on sintering, densification kinetics and evaluation of thermophysical and fracture properties of magnesia doped partially stabilized zirconia (Mg-PSZ), yttria doped partially stabilized zirconia (Y-PSZ) and tetragonal zirconia polycrystal (TZP). These materials have potential application in engineering ceramics[15].

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Krishnaswamy Kasturirangan

Kasturirangan's important contributions relate to high energy astronomy, satellite technology and space physics, to which he has brought to bear his strong background of physics. He has carried out extensive research in X-ray and gamma-ray astronomy through balloon-borne, rocket-borne and satellite-borne experiments. He has also made pioneering investigation of the effect of cosmic X-ray sources on the ionization of the lower D-region of the earth's atmosphere. His system level understanding of a variety of technologies and techniques has enabled him to make significant contribution to the development of satellite technology in India.

X-ray astronomy

Kasturirangan was one of the first few investigators to measure the spectrum of the diffuse component of cosmic X-rays in the medium energy range (20-200 keV) and to critically examine the overall spectral distribution covering both low and medium energy ranges applying appropriate corrections for the effects of atmospheric scattering. Spectral characteristics of the cosmic diffuse background at medium energies are difficult to measure, owing to the secondary background effects at balloon altitudes. He made the first detailed calculations of these background effects. The energy spectrum of the diffuse cosmic background has important implications on the cosmological models of the Universe. He also made the first set of detailed measurements of the low energy atmospheric gamma-ray spectrum including the intensity of the electron-positron annihilation line at 0.51 meV over the equatorial latitudes. Besides providing insight into the secondary cascade effects of the cosmic radiation in the atmosphere, such measurements are

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important to evaluate the medium energy cosmic gamma radiation characteristics from balloon measurements.

Kasturirangan's studies of the time variability characteristics of cosmic X-ray sources such as Sco X-1, Cyg X-1, Her X-1, etc., with balloon-borne, rocket-borne and satellite-borne instrumentation had led to various significant results. These include detection of the change in the spectral characteristics during transition in the state of Cyg X-1 and determination of the hard X-ray spectral behaviours of Her X-1.

Gamma ray astronomy

Kasturirangan has played a key role in conceptualising gamma-ray burst experiment which was successfully flown in the SROSS-C satellite launched by the augmented satellite launch vehicle of (ASLV) of ISRO in May 1992. This payload has certain unique features such as a 256 mil sec time resolution for burst characterisation as well as ability to look at the precursor to the burst for a duration of 65 sec through a circulating memory device. One of the very interesting events discovered through this experiment is an oscillating behaviour of a burst with a periodicity of 237.03 mil sec close to the Geminga gamma-ray pulsar. This discovery, if confirmed, could have important ramifications about our understanding of the physics of young pulsars.

Influence of cosmic-ray and gamma-ray in the earth's atmosphere

Kasturirangan has carried out fundamental investigations on the ionisation effects of cosmic X-ray and gamma-ray in the D-region ionosphere. The important results include: (i) the first quantitative estimation of the perturbation effects of ionisation in the night-time low latitude D-region from the transit of Sco X-1 source, calculation of the corresponding field strength variation in the VLF waves of 164 kHz and comparison of these results with the experimental observations, (ii) theoretical computation on the integrated ionization effects of cosmic X-ray emissions on the low latitude D-region ionosphere and specific predictions on the observability of these effects, (iii) quantitative estimates of the effects of transient X-ray sources and cosmic gamma-ray bursts on the ionisation in D-regions.

Search for a ring around the sun

Kasturirangan provided the basic idea to search for a possible ring structure around the Sun during a total solar eclipse. The experiment carried out during the February 1980 total solar eclipse using an infrared scanning photometer operating

at a wavelength of 2.2 micro metre resulted in the first useful estimation of the mass that could be present in such a ring. Model calculations involving the nature of cosmic origin, its accretion by gravitational field of Sun, formation of ring structure and the thermal characteristics were made by Felton and Morrison only a few months earlier.

Optical observations

Kasturirangan is also pursuing actively studies related to optical variation of the cataclysmic variable stars and X-ray sources. Some of the interesting results include observation of flares on AM CVn, discovery of a flare star near Sirius and detection of an extremely active state of AM CVn.

Satellite technology

Kasturirangan has been one of the key persons in the development of satellite technology in India. He had a variety of important roles in the first Indian satellite, Aryabhata, that included Co-Principal Investigator for the X-ray astronomy experiment, Scientific Coordinator for the two other experiments flown on the satellite, namely, Solar Neutron Gamma-ray detection and aeronomy experiment and Chairman of the Test Programme and Configuration Control Committee for the satellite.

As the Project Director for India's first two experimental earth observation satellites, Bhaskara-I and Bhaskara-II, Kasturirangan provided the necessary technical direction for the configuration development, testing and in-orbit operation of these two satellites. Bhaskara-I and Bhaskara-II carried on-board slow-scan vidicon camera systems and microwave radiometer systems for study of land, ocean and atmosphere. The 1 km resolution imageries acquired in two wavelength bands from the television camera system and the data from the microwave radiometer operating at 19.6, 22.23 and 31.4 GHz frequency bands provided very valuable information for the study of earth resources pertaining to forestry, snow melting, geology, rainfall, oceanography, etc., as well as water vapour and liquid water content in the atmosphere. Bhaskara satellites thus laid the necessary foundation for designing and building the future operational class of remote sensing satellites and also for putting into operation various satellite-based remote sensing applications.

Indian remote sensing satellite (IRS)

As the Project Director of India's first operational remote sensing satellite, IRS-1A, Kasturirangan oversaw the initial configuration studies of the imaging camera payloads, the three-axis stabilised satellite bus, as well as the definition of the ground segment including data processing requirements. This satellite carried two state-of-the-art linear imaging self-scanning (LISS) cameras employing linear CCDs. The cameras were designed to provide imageries in four spectral bands with a resolutions of 72.5 m (LISS-I) and 36.25 m (LISS-II). Placed in a polar sun synchronous orbit, IRS-1A has been a major success marking India's entry into the operational remote sensing system involving indigenous space segment. The spacecraft involved the development of a number of new technologies such as light weight structure, active and passive thermal control systems, power systems including sun tracking solar array and highly sophisticated attitude and orbit control system. The control system employed a zero momentum based four reaction wheel systems, backed up by a hydrazine based propulsion system. The spacecraft employed a variety of sensors such as infrared horizon sensors, gyroscopes, digital and analog sun sensors. The communication system employed X-band and S-band frequencies and involved several innovative circuitry and antenna configurations. IRS-1A compares very well with other contemporary satellites such as SPOT of France and Landsat of US in performance. IRS-1A has exceeded its design life of 3 years and continues to operate even after six years in orbit. Kasturirangan subsequently oversaw the fabrication of the second satellite in the IRS series, IRS-1B launched in August 1991.

Kasturirangan also contributed very significantly for setting up of the ground station for the monitoring and control of the IRS satellite as well as data reception and processing. IRS-1A and IRS-1B are today the mainstay of the National Natural Resource Management System set up by the Government of India to integrate the satellite data with conventional data for a variety of applications in the areas of agriculture, forestry, oceanography, geography, hydrology, land-use, etc.

As Director of the ISRO Satellite Centre, Bangalore, Kasturirangan was directly involved till March 1994, in the development of more advanced satellites, IRS-1C and 1D, which have improved spatial resolution and enhanced spectral domain compared to IRS-1A and 1B. The successful realisation of the indigenous INSAT-2A and 2B was carried out under his direction; the development of more

advanced, INSAT-2C, 2D and 2E have also been initiated. Besides, development of small satellites such as of the SROSS series has been carried out for the conduct of scientific experiments and evaluating new technologies.

Under Kasturirangan's directions new technologies related to satellite development have been initiated including active thermal control system, light weight solar panels, robotics, advanced digital communications, new generation of software for improved orbit determination and new concepts in communication like phased array antenna systems, beam switching, on-board processing, matrix switching, etc. The Indian satellite technology capability has reached a level where it compares very well with contemporary capabilities in developed world.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Jai Krishna

Jai Krishna has been a pioneer in the development of research and training in earthquake engineering in India. Under his leadership, the subject has developed at a very rapid rate and has led to the creation of facilities for undertaking work of earthquake resistant design of structures of all types.

Jai Krishna has the unique distinction of introducing into the engineering syllabi, the first course in soil mechanics in 1948 and structural dynamics in 1958 and initiating research in earthquake engineering in India in 1960[1]. Design work and research on civil engineering structures have been his major concerns. His work has brought in new ideas in the design of earthquake resistant structures leading to economical design and construction practices. Some of his noteworthy contributions include: (a) evolution of simple methods of strengthening brick buildings to resist earthquake forces[2-4], (b) design, fabrication and installation of strong motion instruments in India to collect seismic data for structural design[5,6], (c) earthquake resistant design methods for dams[7,8], bridges[9] water towers[10] and other major structures[11,12], and (d) introduction of the concept of iso-acceleration lines indicative of earthquake forces in epicentral tracts for study of distribution and attenuation of energy[13-15]. Since the common man's dwelling made of brick or stone have been largely responsible for most casualties due to earthquakes, his methods have been adopted on a large scale in the seismic areas of India and abroad.

Another area which attracted his attention was the lack of seismic data for design of structures in the seismic zones in India. This is a field in which still considerable ignorance prevails, since the forces coming on structures during an earthquake are a function of the amount of energy released, the depth of focus, the energy absorbing capacity of the intervening media and the distance from the source of energy. To collect this information, India had to stand on its own feet and instal strong motion instruments in the main seismic zones of the country.

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Under his guidance, a large number of structural response recorder stations have been established in India and sophisticated strong motion accelerographs have been developed; a number of them have already been installed in various river valley projects and other places.

Jai Krishna has carried out special field investigations for 1963 Skopje and 1966 Debar earthquakes in Yugoslavia, 1967 Koyna and 1970 Broach earthquakes in India; iso-acceleration maps were prepared from the study of damage and non-damage of structures, and sliding and over-turning of objects. These studies have helped in establishing a correlation of structural damage with ground acceleration and study of attenuation of ground acceleration away from the epicentre under the influence of local soil conditions. Such studies, supplemented with strong motion instrumental records, help in making precise estimation of ground motion at project sites at various distances from the seismo-tectonic lineaments along which major earthquakes may occur in future.

Jai Krishna has taken a leading part in the field of standardization. The codes of practice for design and construction of earthquake engineering structures developed by the Indian Standards Institution under his chairmanship have helped the country in providing adequate safeguards against earthquake forces. These codes are being constantly reviewed and updated in the light of knowledge and data which become available from time to time under his guidance.

Jai Krishna has given guidance and direction to the international community engaged in earthquake resistant analysis and design, emphasizing each time the need for collection of data and making realistic assessment of properties of materials of construction, so as to predict the dynamic response of structural systems more reliably. The results obtained by many analysts are based on idealized conditions and simplified assumptions. The exact nature of damping and dynamic behaviour of various types of structures and construction materials, ground-structure interaction and ground motion characteristics in different geological terrains are not fully understood and still await solution for evolving better and economic design and construction practices. What is required is intensification of research activity in these spheres and to have adequate data about ground motion by having a close network of strong motion instrumentation. He has actively pursued these ideas and, as a result, two strong motion instrumentation arrays are now being installed, one in Kangra and the other in Shillong region, which are the two major and potential regions of seismic activity in India. Extensive instrumentation in the entire Himalayan belt is also envisaged.

Results of these studies are likely to generate useful seismic data for design in future.

Jai Krishna has suggested that the work carried out so far on brick building should be taken up more extensively and model testing of large size models be done on controlled vibration tables for investigating the actual behaviour of such structures during realistic ground motions. These studies would go a long way in improving the design of such buildings, since the gap between real behaviour and the estimated analytical behaviour is very large in this case. According to him, the direction to be taken by earthquake engineering research should be towards experimentation and scientific modelling of various physical problems to verify the results of sophisticated analytical procedures which have developed over the past few years with the advent of high speed digital computers.

Some of the major gaps in the knowledge on science and technology of earthquake engineering are: (i) relationship between occurrence of microtremors and major earthquakes, (ii) relationship between the energy released by an earthquake at the source and the energy reaching the ground, and (iii) the energy absorption pattern of structures standing on ground in various forms. Intensive research projects to fill these gaps need to be taken up.

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Rangachari Krishnan

Krishnan with his basic education in physics with specialisation in X-ray crystallography has made significant contributions in different branches of physical metallurgy and materials science. His major work has been in the areas of phase transformations, structure-property correlation and in defect structures.

X-ray line profile analysis

X-ray line profile analysis of cold-worked metals and alloys is carried out to determine the state of defect structure in these materials. Krishnan has carried out a detailed comparative study of the various techniques available[1] and has carried out investigations on cold-worked uranium[2], thorium, nickel-chromium, zircaloy-2, etc.

Stacking fault probability studies

Stacking faults in materials is an important class of planar defects and they are studied by X-ray diffraction and transmission electron microscopy techniques. These defects occur normally in close packed structures only.

Krishnan has carried out extensive investigation on a wide variety of FCC and HCP metals and alloys and evaluated the stacking fault energies in these systems. He has shown that in alloy systems if the hcp and fcc phase occur close to each other in a phase diagram and if one works at a composition close to this phase boundary, then on cold-working, one structure could easily transform to the other, indicating that the stacking fault energy is very low[3,4].

Krishnan was also the first one to show that stacking faults can occur in non-close packed structures such as alpha uranium.

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Solid state transformations

Solid state transformations in metals and alloys are effectively used to obtain a wide variety of microstructures in these systems. Their mechanical properties are also consequently altered. Thus study of phase transformations and structure-property correlations in alloy systems becomes an essential component in design of alloys for specific applications. Krishnan has carried out an exhaustive study on phase transformations occurring in a wide variety of zirconium base alloys, titanium base alloys and steels [6-10]. These include martensitic transformations in Zr-Nb, Zr-Ti, Zr-Cu, Zr-Al, Zr-Ta alloys, Ti-6Al-4V and Ti-8Al-1Mo-1V. Based on these studies, Krishnan has shown a good correlation between the type of alloying additions, martensitic start temperature and the type of resulting microstructure—whether it is acicular or lath. Similarly studies have been carried out on active eutectoid decomposition and precipitation reactions in several systems.

Sonar materials

Lead zirconate titanate (PZT) ceramic is used as a sonar material for transducer applications. The piezoelectric properties depend on dopant concentration and microstructure developed as a result of sintering treatments. Krishnan has studied the effect of sintering parameters on the microstructure and properties of PZT ceramics, by measuring dielectric constant, piezo electric strain coefficient and electro-magnetic coupling factor[11]. To achieve fine grain size, it is necessary to use reactive and homogeneous powder. This has also been achieved in his studies in spray dried submicron powders[12]. Krishnan has also studied PZT-polymer composites for hydrophone applications.

Ceramic materials

Structural ceramics such as partially stabilised zirconia play an important role in several high technology applications. Krishnan has studied yttria doped zirconia powders prepared by a sol-gel technique and has shown that the metastable tetragonal phase content is dependent on the size of the crystallites and the concentration of yttria[13].

Krishnan has also carried out extensive studies on the sintering behaviour of uranium dioxide powders in relation to crystallite size in these powders and had studied the inter-diffusion behaviour in UO_2-ThO_2 system by X-ray diffraction studies.

High pressure studies

Krishnan has carried out studies on behaviour of materials like UO_2, UP, etc., under application of high pressure using a diamond-anvil camera in conjunction with a X-ray diffractographic set-up. His notable contribution in this area is the direct evidence obtained by him on how the alpha-omega transformation takes place in titanium[14].

Phase diagram evaluation

As category editor under the Alloy Phase Diagram programme organised by the American Society for Materials, Krishnan has carried out evaluation of a number of tantalum binary systems. In addition to the major areas of research interest listed above, Krishnan has made significant contributions in the study of metallic glasses, superconducting materials, texture studies and radiation damage studies in materials of interest.

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Bhaskar Dattatraya Kulkarni

Kulkarni's scientific contributions are not only in the field of specialization, namely, chemical engineering, but also in the allied scientific disciplines of physics, chemistry and mathematics.

The result of the research work carried out by Kulkarni lie in many areas:

1. The analysis of nonlinear reacting systems
2. Analysing reaction-diffusion behaviour of reacting system and their characterization by perturbation methods
3. Strategies for controlling nonlinear systems
4. Modelling chemically reacting systems by stochastic formulations
5. Using an integer approach to solving coupled algebraic/differential equations
6. Estimating the transport properties and parametric sensitivity of reactors/reacting systems
7. Characterization of reaction/reactor behaviour using the concept of effectiveness factors for heterogeneous systems
8. The mathematical modelling of fluidized bed reactors and their analysis
9. The mechanistic interpretation of experimentally observed features in gas-solid noncatalytic reactions
10. Applications of fractal theory in biological and chemical systems
11. The advantages of conducting reactions in microemulsion media

A summary of the major contributions in each of the above areas is discussed below.

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The analysis of nonlinear reacting systems

In general, the studies carried out in this area by Kulkarni has been towards rationalizing and understanding better the observed behaviour in reacting/reactor systems arising as a consequence of nonlinear mechanisms operating. Special emphasis has been devoted to studying the bifurcation behaviour, stability aspects, and the role of noise in altering system properties. His studies in the area of stability of chemical reactions and reactors have led to the development of some novel concepts such as, (i) feedback of active centres as a possible reason for nonunique behaviour, (ii) nonsystemic autocatalytic rate form to explain exotic behaviour and, (iii) transformation of adsorbed species leading to the concept of a-priori instability. In particular, the new autocatalytic rate model exhibits all the features of the models such as Schlogl, Brusselator, Oregonator, etc., and can be viewed as a viable model for analyzing generalized features of nonlinear reacting systems. The use of normal form equations in simplifying the mathematical model for the highly nonliner exothermic reaction in a CSTR has been shown. Thus the study reveals that symmetries do exist in the solution behaviour of the nonlinear model. This symmetry termed as phase shift symmetry is not easily perceived on analysing the rigorous nonlinear model (i.e., without simplification to its normal form). Numerical results validate the theoretical predictions.

The study and characterization of systems describing chaotic behaviour is a topic receiving considerable research attention in many branches of science. The work carried out by Kulkarni on this topic has been focussed at analyzing the properties of chaos in chemically reacting systems. Thus, the effects of coupling cells wherein it is assumed that each of the cells in its uncoupled state exhibits complex dynamics, e.g., chaos and multipeak periodic has been studied. Coupling of two cells for different initial states, (i.e., chaos-chaos and chaos-multipeak periodic)showed a generalized feature, namely, presence of a hyperchaotic regime at low coupling strengths, followed by a periodic window at intermediate values followed by complete synchronization in the dynamical behaviour of the individual cells as a function of the coupling parameter. The role of initial conditions in achieving synchronization for coupled systems in a situation where one cell is driven by the dynamics of another has also been studied.

Kulkarni has carried out studies which analyze the dynamics of systems with associated time-delays. Typically for a reaction taking place in a CSTR a

simple mechanism for time-delay may be invoked by assuming that there exists a delay in the transport of mass in the recycle stream and studies have shown that their presence can influence reacting system behaviour considerably. In particular, it has been seen that systems with time-delay mechanisms can induce multistationarity, and also possess complex dynamical patterns.

Nonlinear chaotic dynamics are known for their sensitivity to parameter values and initial conditions. It has been recently shown that this feature may be profitably used in reactor operation in terms of improving the conversion/selectivity characteristics for nonlinear reactions. Another method of reactor operation, namely that of periodically reversing the feed flow direction in packed-bed reactors for nonlinear reactions has also been studied. Particular emphasis was laid in studying the bed conversion and selectivity properties. It was found that alternating the feed flow direction periodically can improve the conversion/selectivity behaviour with the added advantage of lower energy consumption.

Analyzing the reaction-diffusion behaviour of reacting systems and their characterization by perturbation methods

Kulkarni has conducted an original analysis of the reaction-diffusion systems for a variety of situations of practical relevance. His studies have led to the development of an original intuitive mathematical transformation that can be widely employed for solving a class of boundary value problems. He was the first to indicate the existence of a new multiplicity pattern, viz,. 1-3-5-3-5-3-1 sequence of states for reaction with nonisothermal effects.

Autocatalytic reaction mechanisms can give rise to a closed chain of actions that generates the feedback necessary for nonlinear behaviour. Invoking the autocatalytic kinetic form wherein the species concentrations affect the reaction rate indirectly via its influence on the reaction rate constant, a model referred to as the *Encillator* has been formulated for conditions when diffusion also plays an important role. A detailed analysis of this model has revealed the rich bifurcation behaviour and stability features the system can possess. Multiple time scale analysis and reductive perturbation techniques near system critical points (leading to the Ginzburg-Landau equation) have also been carried out and the results offer considerable insight into the behavioural features of reaction-diffusion systems.

Strategies for controlling nonlinear systems

Nonlinear systems are sensitive to minor variations in operating conditions, in the sense that the response of system dynamics to changes in the operating conditions can become considerable. Under this constraint, methods for achieving adequate control of nonlinear systems is a topic vigorously pursued. The work carried out has led to the development of a simple nonlinear control method based on an internal model control framework. Its applicability to the control of a rigorous nonlinear process, namely, controlling the pH of solutions has been demonstrated for simple control objectives. Further, studies have shown that the inclusion of an adapting component in a suitable model parameter in the control strategy enhances the robustness of the control method. Studies were again conducted for pH control as well as that for the generic nonlinear reaction engineering model of a continuous stirred tank reactor (CSTR) with a nonisothermal reaction taking place. Simulation results with the control method also showed the excellent capability of the control strategy for both servo- and regulatory control. Interestingly the applicability of the method to eliminate chaotic dynamics and stabilize its operation has also been shown. Importantly, the study showed that the strategy shows five orders of magnitude improvement in the extent of sampling time with speedier recovery to set-points in the presence of modeling errors and also load disturbances in the form of noise.

Methods for controlling chemically reacting systems exhibiting chaotic behaviour employing Poincare sections has been studied. An alternate rigorous method for dynamically controlling the chaotic dynamics on a chosen unstable orbit of the chaotic attractor has also been proposed. In each of these algorithms, the control performance when the real-life process is subject to noise has been studied.

Modelling chemically reacting systems using stochastic formulations

In the area of modelling of reaction/reactor systems, many situations exist when conventional macroscopic models do not accurately describe system features. These situations have been identified and the need for modelling them based on stochastic formulations has been suggested. The conventional macroscopic results are obtained as asymptotic solutions of the more rigorous stochastic formalism. It has also been shown that valuable system information comes out as a natural consequence of the methodology employed. Kulkarni's work on noise induced transitions and origin of oscillations in reacting systems is particularly noteworthy

and fundamental. The major findings have been consolidated in the form of a book that is the first of its kind in the chemical engineering literature. More recently it has been shown that utilizing the phenomenon of stochastic resonance it may be possible to improve upon and also control reactor performance for bistable systems.

Using an integer approach to solving coupled algebraic/differential equations

Kulkarni has recently advocated an integer approach to solving mathematical equation sets in basic and applied sciences. The approach has several advantages and notable among them is the simplicity involved in obtaining solutions, since, conventional steps in mathematical integration are avoided. In particular, many differential/algebraic equations which exhibit complex solution behaviour have been solved accurately. The approach has been applied to both discrete and continuous systems and is based on the theory of indeterminate equations. Interestingly, the roots of the techniques employed have been borrowed from the methods used by Vedic mathematicians of yesteryears.

Estimating the transport properties and parametric sensitivity of reactors/reacting systems

A practical guide with recommendations for the design of packed-bed chemical reactors using the concept of effective transport properties namely, diffusivity and thermal conductivity has been put forth. These recommendations are now widely followed both in industry and R & D work. Further, the use of suitable criteria for identifying conditions when reaction/reactor sensitivities to parameter changes is extreme has been studied for typical Langmuir-Hinshelwood kinetics, commonly employed in catalytic reactions.

Characterization of reaction/reactor behaviour using the concept of effectiveness factors for heterogeneous systems

The concept of effectiveness factor, commonly used as a means of accounting for diffusional effect in gas-solid catalytic and noncatalytic reactions has been extended to gas-liquid reactions. A variety of situations ranging from the simple first-order irreversible reactions to complex reaction network mechanisms have been analyzed using this concept. It has been significantly shown that gas-liquid reactions represent perhaps the most general case, because in its limiting situation it can be reduced to gas-solid reaction behaviour.

The mathematical modelling of fluidized bed reactors and their analysis

Kulkarni has undertaken studies on fluidized bed reactors for complex reactions and shown for the first time that dilution of catalyst with inert solids can lead to substantial enhancement of selectivity in fluid-bed reactors. Strategies for incorporating important system features such as multistep nature of reactions, accompanying volume changes, exothermic effects, etc., have also been suggested. Detailed analysis shows that the inclusion of these features is important in the design of fluidized bed reactors. Noting certain features of the fluid-bed, he has proposed a new mathematical model that has all the rigor and accuracy of very complex models but offers the distinct advantage of simplicity in analysis. This model can therefore be conveniently used for fluid-bed design.

The mechanistic interpretation of experimentally observed features in gas-solid noncatalytic reactions

Kulkarni has proposed a novel concept of delayed diffusion so as to mathematically model and explain the anomalous and interesting feature of chemical reaction starting at the centre of a pellet for important classes of gas-solid noncatalytic reactions. An experimental study using ESCA and NMR for the disproportionation of potassium benzoate to potassium terephthalate has validated the formulated theoretical model.

Application of percolation theory in biological and chemical systems

A number of chemical and especially biochemical systems involve the participation and interactions of macromolecules which are better described as fractal objects. He has proposed the concept of mobile fractals to explain the large enhancement in rates of reactions of such species beyond the limit set by three-dimensional diffusion controlled rates. The concept of fractal dimension has also been employed to map the specific regions on the protein surface and useful structure-property relations have been derived. The growth of bacterial colonies has also been modelled using fractal approach and generalized relations have been obtained.

The advantages of conducting reactions in microemulsion media

Due to their solubilization property, microemulsions serve as excellent media for classes of heterogeneous reactions. Important reacting systems such as nicotine sulphation using sulphuric acid, selective nitration of phenol to *o*-nitrophenol, etc. have been extensively studied by obtaining phase diagrams and microemulsion

characterization. The results of analysis have indicated the specific reasons for improvement in process performance when compared to conventional modes of contacting

One of the most important properties of surfactant aggregates is their role in solubilization process. This allows the investigation of reactions involving sparingly soluble substances as well as water insoluble compounds at the aggregate/water interface. Hence this property has been used in the enhanced decarbamoylation of D(-)N-Carbamoyl Phenyl glycine to D(-)-Phenyl glycine (an important starting material in the preparation of semi-synthetic penicillins and cephalosporins) by its interfacial solubilization under micellar conditions. The local concentration effect, namely, changes in the concentration of ions or solutes in the Stern layer of charged assemblies (micelles/microemulsion) has been exploited to carry out the Backmann rearrangement of Cyclohexanone oxime to caprolactam in dilute acid.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Rajinder Kumar

Kumar has been working in the general area of analysis of multiphase systems. Specifically he has paid special attention to (i) fluid-liquid dispersions from submerged nozzles, (ii) foam bed contactors, (iii) coalescence and breakage of drops in stirred dispersions and (iv) sonochemical reactors. These are briefly discussed below.

Fluid-liquid dispersions from submerged nozzles

Earlier, the phenomena of bubble and drop formation at single submerged orifices were being treated separately. Further, for bubble formation the result reported in literature, as to the effect of different variables, were so divergent and contradictory that their resolution seemed unlikely. Through the two stage model of Kumar and co-workers, it was possible not only to explain why different investigators had obtained contradictory results, but also to predict the actual effects quantitatively. The next step was the development of his unified theory, which could explain both bubble and drop formation through a single set of equations. This model has been widely tested for many divergent systems, like industrially relevant non-newtonian liquids and fluidised beds. The two stage model was then combined with geometric considerations, drainage between bubbles and new models developed for prediction of drop or bubble size in complex distributors like sieve plates and sintered disks. For sintered disks, Kumar's is the only model available in literature.

The model has been recently extended to drop formation in pulsed columns, when they operate in mixer settler regime. The main feature of pulsed column is that there is variable liquid flow rate through the orifices. The model is able to predict not only the number of drops formed during a pulse, but also the sizes of individual drops.

Using similar ideas, it has been possible to propose new models for pneumatic atomisation and nucleate boiling. The model on nucleate boiling simultaneously predicts the bubble growth history and final vapour bubble diameter.

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Foam bed contactors

For the past decade, Kumar has been engaged in the analysis of foam bed contactors, which offer some special advantages for pollution abatement and as a separation device. These contactors are rather complex and the work done on them hitherto has been understandably empirical in nature. By considering the foam to be made up of pentagonal decahedral bubbles, Kumar and coworkers have developed a structural model which can predict the performance of this contactor. It has recently been further tested by them for an industrially relevant reaction viz., the oxidation of sodium sulphide. The model has been extended to include the analyses of three-phase foam beds. The third phase could be a solid catalyst, another liquid in the form of an emulsion or a dissolving solid reactant.

In all the above models one of the parameters required is the liquid hold-up in the foam bed as a function of height. This was hitherto determined experimentally and the values used in the model. Kumar and coworkers have recently developed models for the prediction of liquid hold-up in batch, semi-batch and cocurrent foam columns, by assigning separate roles to the nearly vertical and nearly horizontal Plateau borders, and also by taking surface mobility into account during drainage through Plateau borders and films. A new criterion has been developed and used for modelling the exit foam density in the cocurrent foam columns.

These models of foam drainage considered a foam bubble to be pentagonal dodecahedral in shape. However, this shape is inadequate and the actual foam bubble closely resembles a β-tetrakaidecahedron. Further, Kumar's earlier models clubbed the various Plateau borders together. Recently, Kumar along with a colleague and their students has developed a network model in which each film and Plateau border is considered separately along with its connectivity. The bubbles have been considered to be β-tetrakaidecahedral. This model can be used to test various assumptions made, while developing continuum models. They have already developed a continuum model which closely agrees with the network model, but is much easier to use.

Coalescence and breakage of drops in stirred dispersions

Stirred vessels, though commonly used in industry are very poorly understood even when no dispersed phase is present. When a dispersed phase is present, the transport processes get significantly influenced by the breakage and coalescence phenomena involving dispersed phase particles. Kumar and his colleagues have recently analysed the phenomenon of coalescence of drops in stirred dispersions. They have for the first time, treated the coalescence as due to stochastic variation

of force fluctuations which are responsible for drainage of liquid between drops. The same fluctuations result in either coalescence or separation of drops which are in collisional contact. These models explain some of the interesting observations about coalescence, reported in literature.

A new model has recently been proposed for breakage of viscous as well as non-Newtonian liquids in stirred vessels. This model considers the simultaneous effect of surface tension and the flow in the drop during its deformation through a Voigt model. The restoring force due to surface tension has been assumed to pass through a maximum. The model predicts the maximum stable drop size in stirred vessel as a function of various operating parameters and physical properties of the system. The model is found to be applicable over wide range of variables and rheological parameters.

The breakage of drops in the presence of surfactants in stirred dispersions cannot be explained by existing models. Kumar has successfully developed a model where the difference in dynamic and static interfacial tensions also contributes to the stress responsible for drop breakage. The model predicts the drop sizes over a wide range of surfactant concentrations.

Breakage of mildly viscoelastic drop in stirred dispersions by treating the viscoelastic fluid as glass at the initial stages of the drop eddy interaction which relaxes with time has been successfully analysed. Though the addition of drag reducing agents to continuous phase has been known to yield higher drop sizes in the stirred vessels, Kumar's group has developed a model which can quantitatively predict the drop sizes. The model is based on the assumption that the elongated polymer molecules present in the eddy store up energy, thereby reducing the effective energy of the eddy useful for breakage.

Recently a new framework for the drop breakage phenomenon has been developed by Kumar and his colleague, which considers the breakage due to elongational flow rather then shear flow. This model has the advantage of clearer physics and lesser number of assumptions. The model will also be useful for analysing other systems such as pulsed columns, etc.

When the dispersed phase holdup is increased, the existing models predict the maximum stable drop diameter to increase. Experiments however indicate that after a hold up of about 0.4, the drop size decreases with increasing hold up. To explain these results, two new mechanisms of drop breakage involving the flow field on the impeller have been proposed, which are able to explain these unexpected results quantitatively. This work has also shown that the hitherto

accepted definition of the maximum stable drop diameter as that drop which can no longer be broken by turbulent inertial stresses as inadequate. Instead there are three maximum stable drop sizes corresponding to breakage due to inertial stresses, elongational flow and shear flow, respectively. The maximum stable drop diameter is the least of these three.

The existing models predict that for high viscosity of dispersed phase, the maximum stable drop diameter should be independent of interfacial tension. Experiments, however, not only show significant dependence on it but also show that the dependence on viscosity itself is much lower than predicted by the existing models. A new multistage breakage model, based on deformation and relaxation zones existing in the vessel and the breakage occurring through multiple circulations through these zones has successfully explained these results. The maximum stable drop size for such a situation is the largest sized drop, which cannot be broken by infinite number of passages through the two zones.

The breakage term in the population balance equation not only requires an expression for breakage frequency but also the daughter droplet distribution. All the existing models assume equal breakage. There is no model in published literature for daughter droplet distribution. A new model, based on unequal breakage has been developed, which shows that equal breakage is rare and drops normally break into unequal segments. This model along with the eddy size distribution existing in the vessel, not only yields breakage frequency but also the daughter droplet distribution.

There are a number of models available in literature for coalescence efficiency for drops in stirred dispersions. Though each one considers head-on collision of drops, they predict contradictory effects of different variables like drop diameter, rpm of the stirrer and continuous phase viscosity, because of the difference in details assumed in drainage mechanisms. None of the models explains the effect of dispersed phase viscosity. Kumar and coworkers have recently proposed a new model, where the drops can approach each other at any arbitrary angle. By taking all the details of drainage, like drop deformation and stability of the intervening film, the model is able to predict not only the contradictory behaviours predicted by earlier models, but also predict the effect of dispersed phase viscosity on coalescence efficiency, which could not be predicted by the earlier models. Further, the model is able to explain how turbulence can stabilise dispersions, a result, which had been observed experimentally but had remained unexplained.

Kumar and coworkers have also taken interest in precipitation reactions involving small pools of liquid as in the case of emulsion drops, microemulsions and reverse micelles. They have shown that regular population balance equations are inadequate to describe such systems and have proposed a more general framework which must be employed. They have successfully predicted the precipitation of $CaCO_3$ particles from reverse micelles by considering nucleation with instantaneous growth along with the coalescence rates of the reverse micelles.

Sonochemical reactors

Many interesting reactions, both heterogeneous and homogeneous, are being conducted through the use of ultrasound. There are, however, no quantitative predictions available, based on the physics of the problem. Kumar and coworkers have recently developed a model for homogeneous sonochemical reactor, where they have considered bubble collapse, the temperature attained in the bubble, reactions inside the bubble and in the liquid phase and successfully predicted the formation of H_2O_2 from water through sonolysis.

Technology oriented projects

Kumar has also been engaged in a variety of technology oriented projects which involve technology development, plant design and technical advice. The major contributions made by him in this area are mentioned below.

Copper sulphate directly from chalcopyrites

A highly challenging project successfully completed has been the development of technology for producing copper sulphate directly from chalcopyrites concentrate. The technology was first developed on a pilot scale and then scaled-up to the industrial level and a plant set up successfully.

The roasting of the flotation material in such a way that the temperature could be controlled within ±10°C about the mean value of 600°C, posed the most challenging problem. The reaction is highly exothermic. Fluidised bed proved to be the only solution, which could offer the desired degree of temperature uniformity and adequate contacting time. As the material to be fluidised was minus 200 mesh size, there were special problems with fluidisation. These were resolved by designing a set of three distributors, of varying fineness. Thus the fluidising air got distributed thrice before entering the fluidised bed. Advantage was also taken of the fact that the particle size increases as oxidation progresses and the material fluidises better.

The pilot plant employed a fluidised bed reactor of only 0.75 ft^2. From this, a large fluidised bed of 75 ft^2 distributor area was designed and successfully operated. Such a large scale-up factor (one hundred fold) was made possible through the use of a rectangular bed and dividing the bed into horizontal circulating cells. Other interesting problems solved with respect to the fluidised beds were the location of the feed and discharge points and removal of heat of reactions. This fluidised bed (at the time of commissioning) was not only the largest indigenously designed fluidised bed, but also handled the flotation material which is very hard to fluidise.

Design and setting up of an activated carbon unit

There are many industries producing activated carbon in India. They employ a steam activation process and use rotary furnaces for this purpose. A typical size of such furnaces is about 20 ft. Kumar has designed the largest activated carbon rotary reactor in India, which is double the length of the normal reactor, and one-and-a-half times its diameter. This reactor, apart from having a higher capacity, also yields material of higher activity. The yield given by the larger reactor is also higher as it uses less charcoal per unit weight of activated carbon.

Design of a plant for producing manganese sulphate

A plant has been set up and is successfully operating. The design features of the plant are: (i) an innovative way of reducing pyrolusite using saw dust and (ii) removal of Fe as an impurity in the final product. The present plant produces product of high purity, apart from the commercial grade product.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Raghunath Anant Mashelkar

Mashelkar has made original contributions in diverse areas of polymer science and engineering. His scientific investigations cover modelling of industrial polymerisation reactors, molecular and convective diffusion phenomena in polymeric media, transport phenomena in swelling, superswelling and shrinking polymers and engineering analysis of non-Newtonian flows.

Modelling of industrial polymerisation reactors

The entire process of industrial polymerisation of polyethylene terephthalate (PET) was modelled, thus gaining important insights into the complex behaviour of industrial reactors. The process of melt poly-condensation of PET is accompanied by a desorption of a number of volatile side products (diffusion controlled) accompanied by a series of reversible reactions. This poses conceptual as well as numerical difficulties in modelling. A new FLASH technique was developed to tackle the problem of attendant time variant boundary condition. An apparently anomalous observation of the enhancement of polycondensation rate with increased side reactions, which had remained unexplained so far, was resolved. New strategies for enhancing productivity in industrial reactors emerged as a result of this work.

Mashelkar's model for solid state poly-condensation accounts for degradation reactions, morphological changes and variation of reactive chain end mobility and suggests some unobvious ways of improving the poly-condensation process.

Mashelkar modelled the dynamic changes that take place during the blending of PET melt and the subsequent equilibration of molecular weight distribution (MWD). He took into account the influence of various interchange reactions for the first time. He not only showed their crucial role in reaching a unique equilibrium MWD but also predicted the times required to reach such equilibration, an important factor in industrial operations.

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A comprehensive methodology was developed for the analysis of copolymerization reactors operating at higher levels of conversion, an area of considerable industrial importance. Tools of both deterministic and stochastic analysis were used. The existing conflicts in the estimation of reactivity ratios were resolved. Also, the type of multiplicity and stability behaviour expected in the continuous isothermal and non-isothermal copolymeristion reactors were examined for the first time.

Molecular and convective diffusion in polymeric media

A unified free volume framework for analysis of diffusion phenomena in polymeric systems was proposed through the concept of an altered free volume state (AFVS) model. The model has been used for analysing molecular diffusion in very diverse polymeric systems such as solutions, gels, melts and solid polymers (semi-crystalline, crosslinked or filled). The controversy on the role of microscopic viscosity versus, macroscopic viscosity in controlling the molecular diffusion phenomena for small molecules in polymer solutions was resolved by doing some novel diffusion controlled initiator decomposition studies.

In non-homogeneous deformation fields, macromolecular solutions are expected to show stress-induced migration. Mashelkar's efforts were focussed on studying the mechanism of stress induced migration and its consequences in areas of interest to engineers. A heuristic analysis of stress-induced migration phenomenon was used to provide an interpretation of the anomalous behaviour in areas as diverse as free coating, laminar drag reduction, heat and mass transfer involving viscometric and non-viscometric flows and longitudinal dispersion. A theoretical analysis of the anisotropy and shear rate dependence of molecular diffusivity in polymer solutions as well as probing experiments in carefully designed situations have thrown light on the key issues involved in this important problem. New strategies have been proposed for attacking transport problems involving macromolecular solutions.

Transport in swelling, superswelling and shrinking polymers

Suitably designed polymer networks can swell, superwell or shrink with subtle changes in external stimuli. Mashelkar exploited these phenomena to evolve novel approaches to diffusion modulation in such systems.

Mashelkar devised a new Swellex process (extraction in a swelling polymer) for concentrating macromolecules from aqueous solutions in a semicontinuous mode. He exploited the phenomenon of volume transitions in such networks as well as differences in cooperative diffusion of a network and

that of a small solute in the same network to devise a novel regeneration strategy. The reversible volume phase changes that such swelling polymers undergo were also innovatively exploited for creating bilayered membranes with reversible barriers of controllable sizes. The novelty is that the bilayer can be formed *in situ* and the diffusional behaviour can be tailored at will to the Fickian mode or to the non-Fickian mode. This innovative approach is likely to have important pragmatic implications in the design of new sustained release systems.

Transport of molecules from moderately swollen polymers was studied especially with reference to the coupling of the structural changes accompanying swelling and the attendant diffusion-relaxation reaction problem. Novel strategies were developed to design release of molecules at constant rate. These include tailoring time dependent diffusion, exploitation of erodible crosslinks, etc. The first experimental evidence on the swelling controlled zero order release of a molecule chemically linked to the backbone was reported and explained on a mechanistic basis.

High resolution solid state NMR was used for molecular level investigations in swelling/shrinking polymers. The observation of specific hydration at selective sites of superabsorbers is novel. Carbon-13 nuclear overhauser enhancements were used to demonstrate the movement of the initially absorbed water to the grafted chains rather than to the backbone. Although volume transitions in polymer networks have been extensively studied, Mashelkar provided the first experimental study of molecular level events at the point of volume transition by using thermo-reversible polymers as model systems. Dynamics of internal mobilisation was mathematically modelled and experimentally verified. Some unusual observations in the mobility change in swelling polymers were explained by linking the microscopic events through a macroscopic model.

Engineering analysis of non-Newtonian flows

Mashelkar studied diverse phenomena of interest to engineers in rheologically complex fluids. These cover laminar secondary flows, turbulent flows, free convection and particle motion and deformation. Mashelkar investigated the interaction of inertia and fluid elasticity with special care. He demonstrated that drag reduction can be obtained even under laminar conditions in rotational flows of viscoelastic fluids. His studies on secondary flows of non-Newtonian fluids in helical coils were important early contributions from engineering schools.

In his studies on the motion and deformation of bubbles, drops and solid spheres moving under low and high Reynolds number conditions in rheologically complex fluids, the phenomena of delayed separation in non-Newtonian fluids, new interpretation of the discontinuity in velocity, an original experimental discovery of the presence of dual wakes behind spheres moving in elastic liquids and also anomalous wake formation in liquid drops was reported. Mashelkar's work in mid-seventies provided early data and analysis of macroscopic quantities of interest to engineers.

Dynamics of rapidly stretched films of polymeric solutions was probed by using gas absorption. Contrary to the popular notion that drag reduction phenomenon is associated with a reduction in heat/mass transfer processes, it was shown that the absorption rates could be enhanced on polymer addition in freely falling turbulent films, a finding, which has also an important bearing on delineating different models for mass transfer.

The phenomenon of velocity independent transport in rapid external flows of dilute viscoelastic fluids was explained through a new concept of velocity independent 'elastic boundary layer' by abandoning the conventional ordering arguments in boundary layer analysis. Anomalies in both momentum and heat transport phenomena were explained through the new model.

Mashelkar investigated transport phenomena in very dilute drag reducing polymer solutions (such as turbulent mixing) and helped elucidate the mechanism of action of such additives on a fundamental basis.

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Manohar Lal Munjal

Since 1968, Munjal has been working on different aspects of technical acoustics, including duct acoustics, underwater noise, rail-wheel dynamics, aerodynamic noise, computer-simulation of reciprocating engines and compressors, etc. His significant contributions are in the field of acoustics of ducts and mufflers, which is responsible for the only monograph on the subject in the world, published by Wiley, New York in 1987[1]. He has applied most of it to real-life engineering problems through many sponsored as well as consultancy projects on industrial and automotive noise control. Some of this work is described hereunder.

Frequency-domain analysis of reflective mufflers

Munjal developed an algebraic algorithm for ready analysis of linear dynamical systems[2], and applied the same to develop general design criteria for a rational synthesis of one-dimensional acoustical filters and vibration isolators[3]. For analysis of mufflers, he developed a general transfer matrix method, incorporating the convective effect of mean flow[4].

Transfer matrices for straight-through simple and extended-tube chambers and flow-reversal chambers have been derived making use of the newly enunciated principle of loss in stagnation pressure at the junction. The values of noise reduction predicted therefrom have been verified in the laboratory[1].

The decoupling method for analysis of perforated elements was generalized as an eigenvalue problem and closed-form expressions for the transfer matrix parameters were derived for the concentric tube resonator, the cross-flow expansion element, the cross-flow contraction element, and the three-duct cross flow and reverse-flow elements[5]. Expressions for the perforate impedance in the presence of grazing flow, as required for analysis of the concentric tube resonator, were derived empirically from exhaustive controlled experiments. These transfer matrices have been used to arrive at design curves for the perforated element mufflers[6].

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Analytical expressions for the four-pole parameters for plane wave propagation with an incompressible meanflow have been derived for variable area ducts of the conical, exponential, hyperbolic and parabolic shape[7].

Time-domain analysis of reflective mufflers

Making use of the method of characteristics, a computational scheme was prepared, wherein all the three characteristic variables were calculated by the fixed frame or mesh method. However, this had a weakness in the interpolation scheme and the boundary condition treatment with respect to the entropy variable, which was integrated into a comprehensive time domain simulation of the thermodynamic as well as acoustic performance of a single cylinder engine[1].

Aeroacoustic measurement

Impedance tube method is a standard method in acoustics for measurement of impedance (or reflection coefficient) of a passive termination. However, many difficulties are encountered when it is applied to flow ducts. Ingenious ways were suggested to get over these difficulties. These were then tried on the test bench and suitably modified to develop a foolproof and convenient impedance tube method. In the process, analytical expressions were developed for acoustic dissipation due to viscosity as well as turbulence, making use of flow-acoustic coupling. Making use of this technology, radiation impedance of an unflanged pipe with mean flow was measured for different values of meanflow Mach number, and empirical expressions were arrived at[1].

The method of discrete-frequency-excitation, probe-tube method being too time-consuming and cumbersome, the random excitation, two-microphone, transfer-function method was extended to incorporate the effects of moving medium and damping. An experimental facility, based on this method, has been established in the duct-acoustics laboratory to evaluate the complex reflection coefficient of a passive termination.

A new method has been developed for experimentally determining the matrix parameters of a test element that define the transmission properties with or without gas flow. The results of theoretical uncertainty analyses and many comparative tests have shown that substantial improvements can be expected with this two-source location method over the two-load method, particularly under flow conditions[8].

Source characterization

It has been shown analytically that the source characteristics evaluated by means of the indirect methods (two-load or four-load) are unique, inasmuch as they are

independent of the loads selected, and that the results of the different methods (including the direct method) are identical. General relations have been derived for the transfer of source characteristics from one station to another across one or more acoustical elements and also for combining several sources into a single equivalent source[9]. The linear relationships between the convective source characteristics and their acoustic counterparts have been derived. For the time-variant geometry of the engine exhaust source, the uniqueness criterion is violated, i.e. the source characteristics evaluated numerically, by means of a novel, linear, time-domain scheme as well as the method of characteristics, seem to depend on the loads selected[10].

Lined ducts and dissipative mufflers

In order to design acoustic barriers, enclosures, mufflers, etc., with porous ceramic tiles, the two basic acoustic characteristics required, i.e. characteristics impedance and wave number (both complex) were evaluated by means of three models representing phenomenological, empirical, and microstructural approaches. In order to integrate a lined duct with other muffler elements, source characteristics and radiation impedance, the transfer matrix has been derived for a rectangular duct as well as circular duct lined on the inside with an acoustically absorptive material[1].

Three-dimensional numerical analysis of mufflers

By means of a simple collocation method, the four-pole parameters of the rigid-walled, simple expansion chambers of rectangular as well as circular cross-section for the case of a stationary medium were evaluated[11]. For essentially the same configuration, the variational approach with Hermite polynomial shape functions and the Galerkin weighted residual approach with isoparametric elements have been presented for a truly 3-D analysis of simple expansion chamber mufflers. The core memory requirements and computational efficiency can be reduced by means of the recursive substructuring principle for the repetitive segments of the expansion chamber muffler.

Making use of this matrix condensation technique and the transfer matrix method, a finite element computer program has been developed for the 3-D analysis of the extended-tube expansion chamber as well as simple expansion chamber mufflers. This has been used to evaluate near-field effects in the form of a lumped inertance at each of the two area discontinuities for use in the plane wave analysis right up to the cut-off frequency. Finally, criteria have been developed for the design of expansion-chamber muffler incorporating 3-D effects[12].

Active noise control

An exact analysis of an active noise control system in a duct was done incorporating the characteristics of the primary source as well as the auxiliary source by two different methods; the first made use of standing waves and transfer matrices[13], and the second made use of progressive waves, block diagrams and transfer functions.

For a relatively high-frequency source and/or for ducts with large transverse dimensions, the duct cross-section must be divided into two or more sections. Towards this end, the cut-on frequencies of a large round duct with azimuthal as well as radial partitions were calculated for several modes.

A typical anti-turbulence probe tube was analysed for its acoustic sensitivity or frequency response by means of the distributed parameter approach, wherein mutual interaction of the acoustic pressure fields in the probe tube and the annular duct was considered[14]. Extra noisy fans or blowers would need hybrid noise control systems. Such a system has been analysed by making use of electroacoustic analysis and the transfer matrix method.

Acoustic propagation across multi-layer walls

The four-pole parameters of a multi-layered media for oblique incidence were evaluated. A scheme for evaluation of the complex wave number and characteristic impedance of a plate or tile from its experimentally determined normal-incidence four-pole parameters has been worked out. Starting with the basic equations connecting the state variables of normal stress, shear stress, tangential velocity, and normal velocity, a transfer matrix for a solid plate has been obtained. The general transfer matrix relation has been used to evaluate the response of the plate to be given external pressure excitation on one of the faces. Expressions for the overall reflection, transmission and absorption of the acoustic power of the obliquely incident plane wave have been obtained in terms of the overall transfer matrix of the compound wall[15].

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Bahadur Chand Nakra

Nakra has a strong background in engineering science and has made significant contributions in vibrations of machines and structures and engineering dynamics. Primarily, the work has been concerned with vibration analysis and control, dynamics of pneumatic system, dynamic modal analysis and structural modifications and condition monitoring of machines and machine components.

Vibration analysis and control

Conventional methods of vibration control like avoiding of coincidence between excitation and natural frequencies by mass or stiffness changes, use of vibration absorbers, etc., are not practicable in situations where vibration excitations occur over a wide frequency range, e.g. in aero-space applications. In such cases, use of viscoelastic or polymeric materials in suitable configurations, helps in damping of vibrations through energy dissipation. Constrained layer arrangements are commonly used due to high damping obtainable, though it is possible only under optimum conditions. Nakra[1] suggested the use of dissimilar viscoelastic materials in four and five layer sandwich arrangements, which were through analysis shown to offer considerable improvement over a single layer constrained arrangement. Analysis of forced response of plate and beam arrangements at high frequencies and prediction of damping effectiveness for various families of modes of vibrations, was reported[2] subsequently.

In view of the large number of parameters involved, optimisation studies were reported by Nakra and his co-workers[3,4]. Subsequent work in the area was devoted to doubly curved laminated panels[5] and development of approximate methods for dynamic analysis of complex configurations. Analysis of viscoelasticity damped structures to impact and random excitations, is fairly complex due to the time dependence of stress-strain characteristics and the same has been attempted[6] using a four element model, whose constants have been

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determined by experimental work. The analytical results have also been verified experimentally.

Other applications of viscoelastic damping of significance for which analysis has been carried out by Nakra and his colleagues involve a double stage isolation system giving better performance compared to the conventional isolation systems[7]. In addition, use of viscoelastically damped bearing supports of rotor systems has been investigated and is seen to improve the stability characteristics[8] as well as reduce unbalanced response significantly. Review papers[9] by Nakra on the subject, have been extensively used by researchers.

Pneumatic dynamics

The analysis of railway pneumatic brake systems of vacuum or air-brake types involves analysis for dynamic pressures in a system consisting of number of cylinders connected by pipes and actuators and modelling and computer simulation has been carried out by Nakra and his colleagues[10,11]. This has been done for non-linear multicapacity models and with assumptions of distributed systems and varying capacity effects, as the cylinder pistons move due to pressure changes. The results of theoretical analysis have been compared with experimental results.

Dynamic modal analysis and structural modifications

In this emerging area with applications to vibrations of structures and machines, systems identification techniques have been applied by Kundra and Nakra[12,13] for obtaining dynamic characteristics from experimental data. The technique is especially useful where analytical modelling is difficult, as in the case of a system with joints. The designer of today can optimise his system by interpreting physical hardware modifications in terms of changes in mass, stiffness and damping matrices.

Condition monitoring

Present day trends indicate that it is possible to diagnose possible faults in a machine or machine component by monitoring vibrations, sound and other performance parameters. Sound intensity and acoustic emission techniques have been used by Tandon and Nakra[14] for defect detection in rolling element bearings. Condition monitoring studies have also been carried out by Nakra and his colleagues for machines like reciprocating compressors[15] and centrifugal pumps.

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Roddam Narasimha

Narasimha's major scientific interest may be said to be statistical fluid mechanics relevant to aerospace technology and atmospheric studies, and in particular the evolution, structure, dynamics and control of turbulent shear flows. The phenomenon of turbulence, which he recently surveyed in detail[1], continues to be the major unsolved problem in fluid mechanics. In recent years, the realization has grown that turbulence and other chaotic phenomena present an extraordinary challenge as problems in physics and mathematics as well. "Weather" is also a form of turbulence, but of a particularly complex kind that manifests itself on a rotating sphere in a stratified two-phase medium (condensation of wa :er vapour in the atmosphere can strongly affect the dynamics).

A brief account is given below of major lines of his work in these and other areas.

Evolution of turbulence

Transition from laminar to turbulent flow in a boundary layer, a problem on which Narasimha started his scientific career[2], has continued to engage his attention at various times. The early work was undertaken at a time when a theory proposed by Emmons, that transition occurred through spots (or islands) of turbulence, had made predictions which were not in quantitative agreement with observations from the National Bureau of Standards. Narasimha showed that the chief reason for this was in the assignment of *a priori* probabilities of spot formation, and a new hypothesis of concentrated breakdown, produced excellent agreement among all the observations (including his own). This hypothesis has since been used widely to provide transition models. In recent years, he and his colleagues have investigated the effect of pressure gradient on boundary layer transition zone[3]. A comprehensive numerical model for describing the flow during the transition zone has also been constructed.

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Structure of turbulent flows

Among several studies on the structure of turbulent flows, two are worth special mention.

In one series of investigations what may be called the memory of turbulent shear flows was examined in detail[4]. A carefully devised experiment unambiguously showed the presence of such memory in turbulent wakes, and provided quantitative measures for describing it. The effect was later incorporated into a simple mathematical model for the evolution of the Reynolds stress. Other studies, on a wall jet and an axisymmetric boundary layer, taken together with an analysis of much experimental data gathered elsewhere, led Narasimha to formulate five basic working rules in turbulence[1].

Another aspect of the structure of turbulence is that turbulent energy in boundary layers is generally produced in bursts, whose dynamics are not yet well understood. An experimental study carried out in Bangalore[5] suggested a surprising coupling mechanism between near-wall and outer regions of the flow that might lead to these bursts. This has been the subject of much debate in the literature. Work in the atmospheric boundary layer, carried out by Narasimha and his colleagues, has provided data at huge Reynolds numbers not accessible in laboratory studies, and has shed much light on the scaling of the phenomenon and on the statistics of flux events[6].

Control, relaminarization

Turbulence is generally thought of as the natural state of fluid flow, but under a variety of conditions reversion to the laminar state is possible—a discovery that at first caused much surprise, and is now beginning to find applications. Much experimental work has been done by Narasimha and his colleagues and students aimed at elucidating the nature of this phenomenon, which incidentally occurs in rocket nozzles, wind tunnel contractions, curved pipes and a host of other situations.

Extensive theoretical work has shown that there are three classes of reversion[7]. In the first, turbulence energy is dissipated through the action of a molecular transport property like viscosity or conductivity; in the second, turbulence goes beyond the mere decay of energy to an actual decorrelation of the velocity components contributing to the crucial Reynolds shear stresses that govern the mean flow. The third class of reversion is by domination over slowly-responding Reynolds stresses, exemplified by a highly accelerated boundary layer. Various methods of turbulence management have also been proposed. One

interesting negative result is that, so-called blade manipulators or large eddy breakup devices do not reduce drag in ductflow, as shown by careful measurements carried out in Narasimha's laboratory. These and other forms of turbulence control are likely to become part of the technology in the coming decade.

Atmospheric studies

We live at the bottom of an atmospheric boundary layer normally about 1 km thick. Understanding this boundary layer is important for a variety of reasons, from the quality of the air we breathe to the dynamics of the monsoons. Further, it provides a laboratory for studying turbulence at Reynolds number far beyond the reach of the biggest man-made facilities in the world.

In 1979, Narasimha and his colleagues set up a mast to make measurements at Balasore on the Orissa coast during the International Monsoon Experiment (MONEX). This provided the first measured values of surface fluxes in India. This was followed by an experiment during the total solar eclipse of 1980, when measurements were made at Raichur, using the eclipse as a control provided by nature for switching off radiation for a short while, permitting us to analyse the response of the atmosphere to a sudden perturbation[8]. Narasimha played a major role in conceiving and executing a national project on the Monsoon Trough Boundary Layer Experiment (MONTBLEX), during which simultaneous measurements were made of the atmospheric boundary layer at four stations across the trough, from Kharagpur near the Bay of Bengal to Jodhpur in Rajasthan, during the monsoon months in 1990. The enormous amount of valuable data acquired during this experiment are still being analysed. In particular extensive studies have been made of turbulent bursts in the atmosphere and much new information on their properties obtained.

A recent investigation has concerned the intriguing phenomenon of the lifted temperature minimum. Ramdas and Atmanathan reported in 1932 that on calm clear nights the lowest temperature does not occur at ground but some 20-65 cm above it, contrary to widely held views. Although this phenomenon received observational support from many sites in the world during the 1950s, a satisfactory explanation had proved elusive. Narasimha and coworkers have now provided a full theory which is in excellent accord with observation[9].

Another series of studies has culminated in the formulation of a suitable international tropical reference atmosphere up to 80 km, undertaken at the invitation of COSPAR and now accepted by them[10].

Rarefied gas dynamics

A different line of enquiry that has been pursued over the years in statistical fluid mechanics concerns the solutions of the Boltzmann equation in a variety of conditions. An early and surprising result showed that in an entirely collisionless flow, gradient transport relations could still apply in some special cases, such as for example free expansion of a gas cloud. Correspondingly, in the opposite limit of near-continuum flow, a theoretical analysis of the structure of the distribution function showed that the very fast molecules are in collisionless flow, even though the slow ones are not, leading to peculiar tails attached to the Maxwellian distribution. A problem in which both limits are important is the structure of a shock wave. Several studies here have established the nature of the solution, including one that in retrospect seems like a very early application of the computer[11] for obtaining solutions to the Boltzmann equation. Very recently the structure of a strong shock wave has been investigated using novel group-theoretic tools, which provide an elegant reformulation of the Boltzmann equation as a nonlinear dynamical system[12].

Other studies

The familiar elastic string exhibits some very strange phenomena near resonance. Narasimha's interest in the problem arose from the discovery that the equations then in use for describing such motion were in error; a systematic analysis carried out using singular perturbation methods led to the correct nonlinear equations[13], which have been used widely, most recently to study the nature of possible chaotic motion in a string. A search for mechanical turbulence was indeed one of Narasimha's original motivations for studying the string, but as it often happens, attention wandered away from chaos in a string to turbulence control around that time.

A second line of studies arose directly from Narasimha's close involvement in the investigation of the airworthiness of a civilian aircraft. The best method to analyse this problem turned out to be a Monte Carlo simulation of the fleet as it was actually operated, but the basic features of the problem are encountered widely in other fields (e.g. navigation) and led to the formulation of the concept of a stochastic corrective process[14].

In more recent years, Narasimha helped to formulate aircraft design and construction projects, including the Light Combat Aircraft and, at NAL, an all-composite trainer and the Light Transport Aircraft Saras. He has also promoted the development of parallel computing, at NAL and elsewhere in India, and, with

his colleagues at NAL, obtained the first direct numerical simulation of turbulence in the country[15] on the NAL parallel computer called the Flosolver.

Future directions

The interest in turbulent flows, in technology and in nature, will remain. New experiments to study the dynamics of clouds, which involve a form of turbulence in a heavy two-phase fluid in which nature provides us with beautiful flow visualizations every day, are giving very promising results that should illuminate the nature of the problem of entrainment.

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Rangaswamy Narasimhan

Since the mid-1960s Narasimhan has been engaged in the computational modelling of behaviour[1] which, during the last couple of decades, has grown to be a major study area — especially in the USA under the rubric: "Information processing, approaches to the study of animal and human behaviour". His early work in this area was in modelling visual behaviour[2,3]. He was among the earliest workers in picture processing and scene analysis, who popularized the notions of picture syntax and picture grammars to analyse and describe complex pictures[2].

More recently Narasimhan has been concentrating on modelling language behaviour based on a computational model that emphasizes pragmatics rather than syntax. The underlying principles of this model are discussed at length in a book[4] and are also developed in three lectures given at the "College on the Organization of the Brain" held in Trieste[5]. Some of the implications of this model have been tested in an extended field-study of child-parent interaction in the very early stages of first language acquisition[6]. A critical comparison of this model with some of the other modelling efforts in the study of first language acquisition is to be found in Ref. 7. The general implications to artificial intelligence (AI) studies of this approach to language behaviour are discussed in Ref. 8 Narasimhan's approach to first language acquisition has very close links to the orality-literacy contrast that has been extensively studied by specialists from a variety of disciplines. His ideas on the cognitive implications of orality-literacy were presented at a conference on this subject in Toronto[9]. One principal thrust of his thesis is that language behaviour is indispensable to engage in reflective thinking and reflective thinking, in turn, is of central importance to 'literacy' and to engage in literate behaviour. Schooling must be primarily concerned with teaching children to develop their reflective thinking capabilities. These ideas are developed in detail in Ref. 10.

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The Indian tradition, although it is oral so far as its practice is concerned, is actually built up on a literate substrate. Because of this, the Indian tradition presents many anomalous features. Technical skills (in crafts, performing arts, etc.) usually not available to oral societies are well-developed and within the competence of artists and artisans in India. These features of the Indian tradition are yet to be systematically studied. Some discussions of these features are to be found in Ref. 11.

Finally, the ideas underlying Narasimhan's approach to the computational modelling of behaviour have larger implications[12] to scientific methodology in general. The role of technology in catalyzing social change is a deep subject and its theoretical underpinning is to be sought in the kinds of computational approaches to behaviour that are central to the models advocated here. Some discussion of the limitations of academic science and the historical role played by artisans in promoting technological culture may be found in Ref. 13. Policy guidelines suggested by studies like the ones illustrated in the above summary are exemplified in Refs 14 and 15.

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Bal Raj Nijhawan

Nijhawan returned to India in 1942 after doing PhD in metallurgy from the University of Sheffield in 1941, to organize active metallurgical research and development work during the Second World War. He did internationally acclaimed work on armoured plate development and armour failure and related fields. Subsequently, he worked at the National Metallurgical Laboratory (NML), Jamshedpur, of which he was the Director until 1966, when he joined UNIDO, initially at New York and later at Vienna as a Senior Inter-regional Adviser. In this capacity, he had been engaged for almost two decades in the task of advising many of the developing countries in the development of steel industries and establishment of centres of metallurgical technologies/iron and steel research centres/central metallurgical research and development institutes.

Nijhawan's most prominent work at NML related to, austenitic grain size control of steel, a subject introduced in India by him. In formulating the aluminium solution theory among the host of theories advocated earlier and while investigating it at length, he found it unable to answer and satisfy some characteristics of grain growth inhibition. The work was acclaimed internationally, however, arising from the untenability of the aluminium solution theory in explaining some of the typical characteristics on which sustained research was carried out by him and his colleagues. The results of this work today find almost universal acceptance in the metallurgical world.

During World War II, Nijhawan carried out detailed and systematic investigations on failed Armoured Carriers during storage and war conditions in African theatres, which led to the successful elimination of their disastrous failures.

Another major line of work started by Nijhawan at NML related to the development of substitute families of alloys in which such metals as were not available indigenously (e.g. nickel, cobalt, tungsten, molybdenum, etc.) were to

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be totally or partly replaced by such metals as were available in India (e.g. chromium, manganese, aluminium, etc.); most notable amongst the family of substitute alloys based on indigenous alloying elements (metals) was the research and development work conducted under his leadership on nickel-free austenitic stainless steels based on nickel, chromium, manganese and nitrogen quarternary system in place of nickel-chromium austenitic stainless steels. This work was industrially carried out by him in Belgium and received international recognition and awards besides global grant of Patents in the UK, F R G, France and other Western countries.

Parallel fields of substitution related to the substitution of zinc by aluminium. The process of aluminizing of steel was thus successfully developed, both for steel wire or sheets.

Another major field of activity was Indian foundry sands and bonding materials. An active research group was formed by Nijhawan to investigate Indian foundry sands on an all-India basis and its work resulted in a valuable monograph on Indian foundry sands.

Under the advice of two international pillars of metallurgical research—Charles F Goodeye (UK) and I P Bardin (USSR)—with whom Nijhawan came in close contact in 1957-58, he launched the programme of setting up at NML integrated pilot plants for batch and continuous operations on important metallurgical themes of topical interest to the mineral and metallurgical industries in India. In particular, the low shaft furnace pilot plant set up represents a major highlight of metallurgical research advancement anywhere. The development of alternative processes of iron production with indigenous raw materials regionally dispersed in different parts of India, represents a major field of his metallurgical research interests. Distinct contributions of his group in this area helped to put the NML on the research map of the metallurgical world.

In line with Nijhawan's work during World War II on the development of armour for the Armoured Carriers, much later during 1966, he investigated exhaustively the 80 tons Patton Tank crippled during the 1965 Indo-Pakistan war. This was a major break-through for Indian Tank industry.

Another outstanding achievement was the setting up of the integrated mineral beneficiation plant, the work which has been chiefly responsible for the implementation of the mineral beneficiation flowsheets, agglomeration techniques and pre-dressing and upgrading cycles developed at NML by the Indian steel plants. The integrated ferro-alloy pilot plant has through pilot plant results of

ferro-alloy production trials, helped not only in meeting urgent needs in part of the defence and ordinance plants, but also of the metal industry. The entire work on processing and beneficiation of iron ores for the Bokaro Steel Plant was guided by him under a USSR contract, as also for Tata Iron and Steel Co. and later all the steel plants in India. This work and its results represented the major break-through for the Indian steel industry.

Nijhawan's services to the developing countries during his work at UNIDO covering almost two decades in the fields of metallurgical industries and research and development work in multiple metallurgical fields led to the establishment, in many cases at the Greenfield sites, of 25 Centres of Metallurgical Technologies, Iron and Steel Research Centres and Central Metallurgical Research and Development Centres. All of these are now fully operational and substantially contributing to the substantive growth of metallurgical industries throughout the developing world.

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Mangalore Anantha Pai

Pai has background in both control systems and power engineering. His main contribution has been in using control theory for power system applications. In particular, power system stability, control and computation have been the areas of his research thrust.

Power system stability

The assessment of power system stability by Lyapunov's direct method has several advantages. Its theoretical implications and practical implementation based on the research work around the world, was described in a widely cited book written by Pai in 1981. Since then the topic has been widely investigated and continues to be so because the method is now ready to be implemented in on-line energy management systems. The specific research contributions of Pai have been in showing the validity and limitation of Lyapunov's direct method, develop reduced order energy functions and show the application of vector Lyapunov functions. In dynamic security assessment his method of computing the sensitivity of the energy margin has been used by others with more improvement.

Power system control

Pai and his research workers proposed the use of singular perturbation technique for dynamic equivalencing, i.e., get a reduced order dynamic model of the external system. Emerging control techniques such as D-partition, pole-placement and Kharitonov's theorem were applied to power system control problems.

Power system computation

Use of computers of scale power systems by decomposing the system into smaller subsystems for both load flow and transient stability was proposed by Pai and his research colleagues. Presently he is proposing newer techniques of using parallel processing for power system applications.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Sankar Kumar Pal

Pal's contribution in the field of pattern recognition, in broad sense, lies with the development of theory, formulation of algorithms, and demonstrating their success in real life problems using both classical concept and the concept of fuzzy sets and neural networks. These are described below:

(i) Fuzzy set theoretic approaches have been formulated for pattern recognition and image processing problems when the pattern indeterminacy (ambiguity) is due to inherent vagueness rather than randomness.

The classifiers designed do not need assuming any distribution for the pattern classes. They can process pattern descriptions in terms of membership-function values and handle linguistic input statements based on the theory of approximate reasoning, and provide, unlike traditional decision, natural (soft) output along with its degree of certainty. Their mathematical formulation and comparison with the Bayes classifier have been provided. The role of fuzzy sets as an interface between a linguistically formatted feature and quantitative measurements has also been demonstrated. Algorithms have been developed for determining multiclass (fuzzy) boundary and shape of a pattern class from its sampled prototypes. This reduces and/or represents the uncertainties involved in the conventional crisp procedures. The syntactic classifiers (developed using fuzzy and fractionally fuzzy grammars, and fuzzy primitives) enable one to work with a smaller number of primitives and, unlike the ordinary grammars, to use the same set of production rules and terminals for every class.

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Fuzzy geometry, entropy and other information/fuzzines measures have been used to develop algorithms (together with mathematical framework) for image segmentation, edge detection/enhancement, primitive extraction, skeletonization and clustering to result in both fuzzy and crisp output. This avoids committing oneself to a specific hard decision for ill-defined input. Its extension to hybrid coding and colour image processing has also been made.

The aforesaid measures for spatial ambiguity and grayness ambiguity have been optimized to provide quantitative indices for image processing operations and feature evaluation problems, in order to avoid visual subjective judgment on image quality (and human intervention) by making the task objective.

(ii) Various fuzzy set theoretic operators/tools have been defined, in order to make the task of analysis and recognition effective. These include, correlation between membership functions, new generalized definitions of union, intersection and inclusion operators (considering the sense of membership function and measure theory), index of area coverage (IOAC), fuzzy medial axis transformation (FMAT), bounds for membership functions and spectral fuzzy sets. The bound functions and spectral fuzzy sets enable to reduce the uncertainties in assessing membership value and to make the fuzzy set theoretic approach enough flexible. FMAT is useful for both skeleton extraction and exact reconstruction/representation of images.

(iii) Concept of fuzzy sets has also been incorporated at various stages of Kohonen's network and multilayered perceptron to handle imprecise, incomplete or linguistic input data and intractable pattern classes for recognition, rule generation and inferencing, and for extracting objects from noisy images. This shows how pattern description in terms of linguistic properties and membership values can be processed by a neural net for fuzzy and crisp classification, and the merits of neuro-fuzzy approach over conventional networks and Bayes' classfier.

(iv) Neural networks (NN) have been used to find the maximum-a-posterior (MAP) estimate of a scene modeled as a Gibb's random field. The MAP estimation problem which is computationally

prohibitive has been solved using a modified version of Hopfield's neural networks. Relaxation algorithms for object extraction have been developed, which optimize objective functions that can be mapped as the energy function of a Hopfield type network and Kohonen's self-organizing network. These algorithms work well in noisy environment. A probabilistic model for investigating robustness of NN systems under component failure has been developed, where the failure process is governed by Poisson distribution.

A connectionist model, called X-tron, along with supervised and unsupervised learning algorithms has been developed for perception of mixed objects. Its utility for building psychologically motivated system for occluded object recognition has been established.

The problems of getting stuck to local minima of the multilayer perceptron, the heuristic selection of cellular neural networks' parameters and automatic selection of optimal image enhancement operators have been solved using genetic algorithms. A new mutation operation called directed mutation has been developed in this context, which accelerates the rate of convergence of the genetic algorithm.

(v) New definition of classical entropy based on exponential behaviour of gain, and the definitions of various image entropies have been introduced along with their properties. The image entropy measures include local, conditional, positional, hybrid and higher order fuzzy entropy. These information measures take care of the dependency of pixel intensities, probability and possibility distributions of pixel, collective pixel property and location of an object in the scene. Various algorithms for quantitative scene analysis and robot vision problems have been developed using these measures.

(vi) A new concept of self-supervised learning (GGA) based on generalized guard zone has been introduced along with its stochastic convergence, dynamic behaviour, and automatic selection of threshold (optimum dimension of guard zone) and its bounds. In the absence of an external supervisor or any higher level knowledge, the system can reject the outliers (doubtful or mislabelled samples) from the parameter estimation procedure, thus providing always an improved performance as compared to usual non-supervised

recognition. This is useful in classifying and training a machine (or a neural network) in presence of noisy (or doubtful) samples, particularly when the size of initial training set is very small.

(vii) The problem of extracting automatically the valid edge points from the conventional edge output has been tackled using the characteristics of human visual system. This characteristic also provides contrast and homogeneity measures of image regions for their extraction. Formulation of approximate but efficient methods of image coding using quadratic Bezier approximation technique and Bresenham's polynomial constitutes another part of contribution.

(viii) The aforementioned theories have been demonstrated for recognition of speech, speaker, skeletal growth of children from X-ray, abnormalities in brain neurosecretory cell, hand written characters, finger prints, targets of defence interest from satellite imagery, various rocks from landsat imagery data and mango varieties from their leaves under various projects of national importance.

(ix) Research is continuing on the implementation of these theories for the management of uncertainty in space station autonomous operations (e.g., space shuttle proximity operations, satellite servicing and camera tracking in orbital operation, and Mars rover control for sample collection), where the tasks of pattern recognition interact with and support the control problems. The objective is to support unmanned mission by modeling the human capability of common sense reasoning in decision-making tasks. User friendly working systems for image analysis have also been built in NASA/JSC under his direction.

Pal's contribution is significant from both theoretical and practical points of view. At a conceptual level, he has shown how the concept of fuzzy sets can be exploited in handling uncertainties at various stages of a recognition system e.g., in representing linguistically phrased input features for processing, in weakening the strong commitments for extracting ill-defined image regions, primitives, properties and relations among them, in providing image information measures, in providing an estimate/representation of missing or contradictory information and multi-class membership of ambiguous patterns, and in neural learning by linguistic and partial input. At a practical level, his systems have become very

useful for developing the interfaces of fifth generation computer systems, for diagnosis of skeletal and cancerous growth, for estimating geological resources, for supporting unmanned space missions, for forensic investigation, and for robot vision and remote sensing applications (where frequent human interruption and subjective judgment on image quality is not possible). It is also noteworthy that his fuzzy set theoretic research has led to the emergence of a new discipline in its own right with the creation of new theories.

Pal also has built an active research school on pattern recognition and artificial intelligence, which has recently been recognized as a separate department called machine intelligence unit at the Indian Statistical Institute.

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Lalit Mohan Patnaik

During the last twenty two years of his professional service, Patnaik has made several significant contributions to the broad discipline of computer science and engineering. His substantial contributions are on the theoretical, software and hardware development aspects. Of specific mention are his novel contributions to computerised industrial automation, parallel processing, distributed computing, real-time systems, neural networks, genetic algorithms, and symbolic computation.

Computerised industrial automation

During early seventies, Patnaik has undertaken the challenging task of modelling, optimization, parameter identification, and development of multivariable computer control algorithms for the on-line control of a complex system, such as an ammonia reactor which forms a key component of a fertiliser plant[1]. He has developed discrete multivariable control algorithms for an operating plant in India. His extensive hybrid computer simulation techniques have demonstrated a significantly improved yield of the operating plant. He was also involved in the development of highly efficient self-tuning control algorithms for nonlinear multivariable systems[2,3]. These studies undertaken by him have thrown new light on the development of efficient digital control algorithms amenable for implementation on cheap off-the-shelf microprocessors. The algorithms and software packages developed will be useful for the real-time control of other complex nonlinear multivariable dynamic processes operating in uncertain environments.

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Parallel processing

Patnaik's work on several aspects of parallel algorithms and parallel architectures has broken new ground in these areas. During the past decade, he has been concentrating on the development of concepts of science of parallel computation. This work is driven towards the understanding of basic characteristic features of specific applications that yield the best performance on specific parallel architectures. One of the challenging issues in parallel processing is to find out the best possible mapping of applications/algorithms in to various parallel architectures. Towards this goal, his research in parallel processing during the last decade has focussed on parallelizing diverse applications, such as scientific visualisation, numerical computation, transaction processing, computer-aided design of VLSI systems, neural network simulation, genetic algorithm-based optimization, and symbolic computation. In order to pair algorithms and parallel architectures for best performance, he has carried out extensive studies using three approaches, (i) analytical studies on parallel algorithm design and performance evaluation using queuing theory, Petri nets and Markov chains, (ii) experimental studies on test beds built using 16 and 32 bit microprocessor chips. Such a three-pronged approach enables the validation of the analytical and simulation techniques by comparison of the results obtained from these methods with those obtained from the experimental test bed.

In the area of parallel processing, Patnaik has developed novel systolic algorithms to evaluate polynomial equations[4,5]. These are encountered in a variety of problems in signal and image processing, computer graphics and numerical computation. These architectures have been developed very ingeniously, such that they are amenable to VLSI implementation. He has proposed a significantly novel dataflow architecture called EXtended MANchester dataflow architecture to provide improved performance compared to the original Manchester dataflow architectures[6].

In order to come up with a highly efficient message passing architecture, Patnaik has proposed an intelligent configuration of hierarchial network of hypercubes called extended hypercube[7,8]. This architecture performs much better than other related message passing architectures in terms of fault -tolerance, utilization factor, degree and diameter of the network, ability to solve problems involving total exchange and multinode broadcast. This architecture has been implemented using T800 transputers and problems from the domain of robotic

motion planning based on various neural network models have been studied on this architecture to demonstrate its improved performance.

Hidden line and surface removal, ray tracing and radiosity, curve and surface generation are significant problems with good appetite for number crunching. These algorithms have been intelligently parallelised to yield significantly improved speedups on parallel architectures such as multiple instruction multiple data (MIMD), hypercube, dataflow and pipeline processors.

Computer aided design of very large scale integrated (VLSI) circuits involves a number of compute-intensive steps, such as (i) placement and routing, (ii) simulation at the circuit, logic and switch level, and (iii) testing and fault simulation. To accelerate the design process, efficient parallel versions of the simulated annealing algorithm have been designed and mapped on to a number of parallel architectures to yield significantly improved performance. Simulation of a VLSI circuit involves the solution of a large number of coupled nonlinear ordinary differential equations and this process is extremely time consuming. The waveform relaxation-based algorithm has been parallelized and mapped in to a hypercube architecture to significantly reduce the circuit simulation time. Prior to parallelizing the simulation phase, the circuit partitioning phase has been parallelized using simulated annealing and has been mapped onto the same hypercube architecture. Logic and fault simulation algorithms have been mapped onto message passing architectures, such as a distributed network of workstations and CDAC's transputer-based machine PARAM.

Evaluating the performance of parallel architectures is a very important phase in the design and development of new parallel architectures. Patnaik has developed software simulators for a variety of parallel architectures based on SIMD, MIMD, pipeline, hypercube, mesh, dataflow, and connection machine principles. It is essential to study the performance of such architectures combining the principles of reliability. For such studies on performability of hypercube and mesh architectures, he has adopted the generalised stochastic high level Petri nets to study the performance and fault-tolerance characteristics with different routing techniques. Hybrid computer simulation of queuing system dynamics has been attempted to yield faster simulation of parallel architectures[9].

With program development and verification as the principal objectives, Patnaik has considerably extended the notions of functional programming (FP)

and has worked on choice nondeterminism and inter-program communication in certain extended and modified versions of FP systems, called nondeterministic FP Systems (NFP)[10]. These studies will have a significant impact on the specification and verification of programs for parallel and distributed computing systems.

Distributed computing

Patnaik has developed novel locking-based concurrency control algorithms with improved concurrency for distributed and centralised databases exploiting the semantics of read-only transactions and has carried out extensive performance evaluation studies of these algorithms using graph theory formalism and simulation studies. The distributed concurrency control algorithms presented are resilient to site failures and/or network partitioning. Three semantics of read-only transactions are defined. They are, (i) serializability, (ii) weak consistency, and (iii) semiweak consistency. In another study by him, concurrency control algorithms using object oriented paradigm have been designed. Interesting reduction techniques have been developed to simplify complex, large Petri nets[11] and such techniques have been adopted to specify, design and evaluate the performance of protocols for onboard computing systems such as those encountered in Insat II satellites. Characterising the strengths of processors, efficient load balancing algorithms have been developed for a fault-tolerant distributed computing environment[12].

Real-time systems

Hard real-time fault-tolerating computing of distributed systems is a challenging area involving several issues of algorithm design and performance evaluation to meet the stringent timing requirements. Patnaik has proposed a significantly improved version of Petri nets called S-nets[13] to carry out the schedulability analysis of such systems and has applied them to onboard computing systems of Indian satellites. Novel rollback and recovery algorithms have been developed by him for fault-tolerant real-time distributed computing systems to yield improved fault-tolerance capabilities and these techniques have been employed to the distributed computing systems of onboard satellite launch vehicles.

Specification and verification of real-time systems assume significance for the design of complex systems. In case of real-time systems, timeliness is an important criterion other than functional correctness. Novel temporal logic-based techniques have been developed for the specification and verification of real-time

distributed computing systems, using partial order framework and these techniques have been applied to several real-time control systems such as computer integrated manufacturing systems. The specification environment consists of two formal languages to describe the real-time behaviour of systems at the requirements specification and systems specification levels. A set of tools is also developed to reason about the specifications. A modal logic called distributed logic (DL) is developed for system specification.

Symbolic computation

Symbolic algebraic computation has recently attracted increasing interest in computer science, mathematics, and a wide spectrum of application areas. Analysing certain symbolic algebraic computation algorithms and characterizing their dynamics are sometimes difficult by using the standard tools of classical computation and complexity theory. Patnaik has meticulously performed two characterizations of Buchbager's Gröbner basis reduction algorithm. These are the dynamical system characterization and the type 2 characterization and it is hoped that these novel characterizations proposed by him will provide a new framework for studying the poorly understood rich and complex dynamics of the algorithms in symbolic algebraic computation. He has also undertaken a software experiment towards studying the dynamics of the Gröbner basis reduction in commutative polynomial rings of two variables. These experiments will prove very useful for the development of software in scientific visualisation. He has also parallelised these algorithms for the domain of symbolic computation and mapped them in to message passing architectures such as hypercube.

Artificial intelligence

Patnaik has made interesting contributions with practical emphasis in the area of diagnostic reasoning with surface and deep level knowledge in medical domain. The aim of this work has been to structure the domain knowledge based upon some conceptual models, so that the knowledge can be efficiently used for diagnostic reasoning in medical domain. Two expert systems based upon models for diagnostic reasoning and deep level knowledge have been developed. A model has been proposed to organise the disease category knowledge around multiple taxonomies. This system INTERX has been implemented in UCI-LISP on a DEC-1090 system for the domain of infectious diseases. The second system diagnoses diseases using the deep-level pathophysiological knowledge of the disease mechanisms. The behaviour of such a complex system is generated through a

predictive analysis, using processes, and is represented as causal networks of disease states of structured locations. This system DIAN is also implemented in UCI-LISP on a DEC-1090 system for respiratory tract infectious diseases.

Expert systems have also been developed for the domain of VLSI synthesis and printed circuit board layout.

Neural networks

Patnaik has studied various issues related to the suitability of message passing architectures for simulating neural networks. Performance analysis of ring, mesh, binary tree, hypercube, hypernet and extended hypercube architectures for simulating artificial neural networks has been carried out. These studies reveal that the performance of the extended hypercube, a hierarchial interconnection network of hypercubes, is better than those of ring, mesh, binary tree, hypernet and hypercube topologies for simulating ANNs. The performance of the neural network simulator implemented on the hierarchial network of hypercubes was measured in terms of CUPS (connection updates per second) and the same was compared with the CUPS ratings obtained on Connection Machine-2 and Intel's WARP machine. The extended hypercube architecture proposed by him performs much better than these two machines in terms of CUPS rating.

Parallel implementation of backpropagation network and bidirectional associative memory (BAM) on various topologies has been another significant contribution. Different transputer-based parallel architectures have been chosen as the platform for simulation. The BAM has been implemented on transputer-based topologies like hypercube, mesh and linear array. The speedup and utilization of these topologies for varying number of transputers and varying number of neurons in the layers are found out. The hypercube topology gives better speedup and utilization factors compared to mesh and linear array. The backpropagation network has been implemented on a linear array and ring of transputers. Speedup is obtained during learning and recalling operations on varying number of transputers. The ring network performs better during the learning operations and the linear array performs better during the recalling operations.

The BAM and backpropagation networks have been used in the field of numeral recognition. The concept of multiple training and dummy data augmentation have been used for increasing the storage capacity of the BAM. A condition for multiple training the BAM for many patterns is discussed. A

comparison is made between BAM and backpropagation network for numeral recognition under noisy conditions. The backpropagation network is found to be a better classifier in the presence of noise. This network has also been used in the field of medicine for diagnosing arthritis and related rheumatic disorders. The network is able to identify and classify various arthritis and allied rheumatic disorders.

Classification and recognition of objects are needed in practical applications such as automation of assembly lines. Difficulties in the recognition of objects encountered in a typical assembly line are due to the lack of a fixed orientation or position of the objects. The drawback in the conventional pattern recognition techniques is the enormous time and computational overhead required for classification. But the conventional techniques are well-suited for extracting the features of objects. Patnaik has developed a method for the classification and recognition of objects under change in position, orientation and scale. He has combined the advantages of both the traditional pattern recognition methodology and the neural network paradigm for the distortion-invariant object recognition. The traditional pattern recognition techniques are used for the extraction of the features of objects. To extract the invariant features of objects, geometrical moment-invariant techniques are made use of. In the case of multiple objects, segmentation of each object before extracting the features is carried out. Six non-linear functions are generated using the moment-invariant feature extraction technique and they are fed as input to a multi-layer perceptron. Backpropagation learning algorithm is used for training the network.

Signatures are widely being used as a credible mechanism to verify the identity of persons. Signature of a person is highly individualistic and has unique characteristics, which are very difficult to forge and hence provide a good and simple method for personal identification. Patnaik's work investigates the feasibility of employing the neural networks to the problem of identifying human signatures. Conventional approaches of signature recognition using template matching techniques are unreasonably expensive, in terms of the amount of computations and searching required, particularly when the data bank of the pattern templates is of large size; as is the case in commercial places like banks. Neural networks on the other hand are elegant, cost-effective and are easily implementable in such applications. The problem of signature recognition using a

multilayered neural network with the backpropagation learning algorithm has been studied with very good performance.

Testing for a fault in a digital circuit involves establishing a relationship between the primary inputs and outputs. Test patterns used to detect faults in a digital circuit need to accomplish two objectives, viz., (i) controllability and (ii) observability. Controllability involves, driving a line which is faulty due to either stuck-at-1 or stuck-at-0 faults, to its opposite logic value. Whereas observability involves observing the logic value of a line, internal to a circuit by looking at the primary outputs. In Patnaik's work, the performance of the diagnosing procedure using the ART-1 algorithm and its modified version have been discussed. It is shown that the modified ART-1 algorithm increases the diagnostic resolution of the fault locating procedure. The results obtained are then compared with an existing testing methodology called built-in self test (BIST). The main disadvantage of the BIST methodology is the large number of test vectors generated. By employing this procedure, it is possible to test and locate faults in a more efficient manner.

Genetic algorithms

Genetic algorithms are populationary search and optimization techniques based on the principles of natural evolution. Darwin's 'survival of the fittest' principle, along with genetic recombination, form the driving forces of genetic search and optimization. The last five years have witnessed the reemergence of genetic algorithms (GAs) as general purpose search mechanisms with applications in a plethora of real-life domains.

The focus of his research on GAs has been both the practical and theoretical aspects of GAs. On the theoretical front, models of the dynamics of GAs, both exact and approximate, have been developed[14]. These models have been implemented as GA-simulators, and have been usefully employed to understand issues such as deception in GAs. Specifically, the idea of binomially distributed populations (BDPs) has been introduced and various properties of these BDPs have been mathematically characterized. The effects of the genetic operators on BDPs have been exactly modelled, and these models have been shown to be efficient when employed to simulate the behaviour of genetic algorithms. As the complexity of the problem increases, even this model becomes computationally too expensive. This factor has led to investigate other

approximate models that are affordable in terms of computing time. The notion of fitness moments has been introduced as the basic foundation of this approximate model. Once again the validity of the model has been corroborated with emperical results.

On the practical front, his contributions can be categorized into two classes: (i) new techniques to improve the performance of GAs, (ii) applications of GAs to real-life problems. The adaptive genetic algorithm (AGA) and the controlled disruptive genetic algorithm (CDGA) have evolved from Patnaik's pursuit for improving the performance of GAs. Both employ an adaptive strategy at determining the mutation and crossover probabilities, to broadly realize the goal of simultaneously improving the exploration and exploitation capacities of the GA. Emperical evidence points to the considerable superiority of these variants of the standard GA, specially of the AGA.

A different line of attack has been employed in realising improved versions of parallel and distributed GAs. A new variant called the extended distributed GA, which tries to exploit the merits of both parallel and distributed GAs has been realized.

The acid test for any optimization and search method arises when solving real-life problems. Automation of VLSI CAD techniques abounds with NP-complete problems, and they provide stiff challenge to any optimization approach. Patnaik's focus has been on the test generation and channel routing problems. For both the problems, appropriate cost functions have been designed, and the genetic approach has been validated on standard benchmarks (ISCAS-85). For the channel routing problem, efficient genetic operators have been developed and validated. His research demonstrates that the genetic approach is indeed a viable alternative to other classical approaches for solving these problems, including the simulated annealing paradigm.

Nonlinear dynamical systems

Patnaik's recent work on the dynamics of nonlinear systems driven by coloured noise has broken new ground[15]. Such systems are encountered in a wide variety of areas including physics, chemistry, natural sciences, and engineering. Particular emphasis of this work has been on the extension of the effective Fokker-Planck equation (EFPE) formalism and the fluctuating potential theory to study the dynamics of bistable systems driven by coloured noise. An EFPE using the path

integral formalism has been derived. Excellent agreement is obtained between the mean first passage time computed using the adiabatic approach and that of the numerical simulation results. Interesting similarities between the usage of the adiabatic approach to the stochastic resonance phenomena and the usage of the adiabatic approach to the bistable system driven by coloured noise are brought out.

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Surendra Prasad

Surendra Prasad has worked in the broad area of signal processing and communications. His major contributions are summarized in the following.

Optimum receivers for analog communication

The problems of optimization of the receivers for various kinds of analog modulation schemes were of great interest in the late 60's and 70's. The motivation for this research problem was provided by some interesting developments that were taking place in the estimation theory literature at that time. First, a state variable based Markovian representation of signals had been shown to be eminently powerful for the development of optimal, recursive filtering algorithms for processing of noisy signals. Simultaneously, it provided a unified framework for the development of recursive algorithms not only for prediction and filtering, but also for smoothing, which, for the price of a nominal but fixed lag between the observed and processed (estimated) signals, offered the possibility of a significantly improved performance in terms of mean squared value of the estimation error.

Surendra Prasad and coworkers therefore, proceeded to carry out a formal derivation of a new class of analog demodulators, called by them as fixed-lag demodulators, for the various linear and nonlinear modulation schemes on the one hand, and their performance analysis on the other. Stable, realizable structures were proposed, which through the introduction of a nominal delay in the receiver, could yield the ideal performance of the unrealizable infinite delay receiver. An in-depth performance analysis further showed that the required lag is of the order of the time constant of the message signal of interest for the case of linear modulation schemes like AM and PAM, but could be considerably smaller for

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nonlinear modulation schemes like FM and PM, if associated with a large modulation index. Later this work was extended in several interesting directions.

MTI filters

An MTI filter is used in a radar system to eliminate clutter arising from undesired echoes from stationary objects. The classical MTI filters consist of simple, single delay line or double delay line cancellers. The performance of MTI filters is usually measured in terms of the improvement factor, defined as the ratio of the signal to clutter ratios at the input and output, respectively. While, the conventional MTI filters are able to reject stationary clutter very well, they are not very effective against certain moving sources of clutter, such as that due to clouds and trees, which cause a spread in the clutter spectrum.

Some reflection on the existing works on the optimization of MTI filters led us to two conclusions: first, that it was important not only to optimize performance against moving clutter, but also desirable to do so without sacrificing performance against stationary clutter, which in most situations is likely to constitute the major component of the total clutter power. Secondly, it would be desirable to optimize MTI filters against moving clutter without making detailed assumptions regarding the clutter power spectrum, in order to make them robust to variations in the nature of the clutter. For the first objective, a constrained optimization problem was formulated, which, while carrying out the required optimization of the MTI filter against moving clutter, could also guarantee a complete elimination of the stationary clutter. It was shown that the design of the new MTI filters could be carried out via the solution of a modified eigenvalue problem, involving the clutter covariance matrix **R**, an appropriate projection matrix **P** ensuring the null at the fixed clutter frequency, and a visibility region matrix **B** specifying the visible region of interest for the target doppler. Surendra Prasad and coworkers, showed that the optimum filter coefficients are given by the eigenvector corresponding to the smallest eigenvalue of the modified eigenvalue problem:

$$\mathbf{PAPx} = \lambda\mathbf{PBPx} \qquad \text{... (1)}$$

With the help of this theory, it became possible to design a variety of MTI filters having these features and yielding large improvement factors in the presence of both moving and stationary sources of clutter.

For the second objective, an analytical approach was proposed, which required only some broad specifications like the bandwidth of the clutter spectrum. This solution was based on a worst-case design approach, in the sense that it tries to maximise the improvement factor corresponding to the most unfavourable clutter characteristics satisfying the bandwidth constraint. A Gabor-like notion of bandwidth for discrete-time sequences was used to formulate the worst case design problem again in terms of the eigenvectors of a simply constructed tridiagonal matrix. It was shown that the approach could be used for both regular PRF and staggered PRF MTI radars. Further the worst-case improvement factors were found to be comparable with those obtained for a specifically optimised solution.

CFAR detection

Another problem arising in the detection of radar signals is the variability in the properties of noise and clutter in terms of their spatial and temporal power distribution. System design in such situations usually requires the maintenance of a constant false alarm rate (CFAR) in the automatic detection of a target. The problem of designing CFAR detectors for arbitrary variations in distributions and/or power levels, however, has been an open question, and, in fact, remains so to this day. A contribution to this problem was made by way of developing an adaptive detection procedure, by which the detection threshold is so adjusted as to provide an asymptotic false alarm rate that is approximately invariant with changes in radar clutter return amplitude pdf's in a broad class. The usefulness of the method was demonstrated for the Rayleigh, the Weibull and the log-normal pdf's.

Automatic equalization

Automatic equalization of dispersive channels is crucial in obtaining reliable performance from a digital communication system. Dispersion in the channel causes intersymbol interference, which causes a reduction in the noise margin and a consequent increase in the error probability. Although the ultimate performance criterion of interest here is the error probability, equalizers are usually optimized using a minimum mean squared error or peak distortion criteria.

Intrigued by an interesting observation that, when the signs of the alternate terms of a symmetric discrete-time series are reversed and the resultant series convolved with the original, the newly created time series has alternate values

equal to zero, Surendra Prasad and coworkers argued that this could provide a rather convenient method for implementing a zero forcing equalizer of the adjust and freeze type. It turned out to be rather simple to work out the details of such an arrangement, which would apply to both the Nyquist as well as partial response type pulses used for bandwidth efficiency. The performance of these equalizers was shown to be very close to the optimum for a variety of situations.

Later, motivated by a desire for realizing efficient structures for equalization, the possibility of developing some state-space structures for the same was considered. This led to a new state space formulation of the problem, in which the transmitted data are modeled as a white noise sequence estimation from the noise corrupted output of a linear system. An important advantage of this approach of equalization is shown to be that the order of the required state space model can be made significantly smaller than the length of the impulse response of the channel, thus resulting in savings in computations.

Seismic signal processing

Of the various steps that go into processing a seismic trace, the deconvolution step forms the key to its successful interpretation. A seismic trace is obtained by exciting a section of the earth's surface by a finite duration seismic wavelet (via an explosion or an airgun) and recording the reflections from the subsurface layer structures, in order to reconstruct pictures of these layers and identify structures which can trap oil or other resources. The recorded seismic trace y_k, however, comprises a superposition of the reflected seismic wavelets from various layers, along with noise. Thus, one can write

$$y_k = z_k + n_k \qquad \text{... (2)}$$

where n_k is the noise component of the measurements and z_k is the true reflection signal. A simple model for z_k is the following convolution relation

$$z_k = \sum_{j=1}^{\infty} a_j b_{k-j}. \qquad \text{... (3)}$$

where a_j represents the reflection coefficient of the jth layer and b_k represents the sampled values of the seismic wavelet used.

Identification of the reflectivity sequence comprises the deconvolution problem, which is usually an ill-conditioned one in the best of situations, and

complicated further in offshore explorations due to the presence of multiples and reverberant reflections.

The standard method of predictive deconvolution, however, works well only for stationary data and requires a large order predictor for effective deconvolution. A closer look at the nature and generation mechanism of this data suggested, that the methods of adaptive filtering should prove to be of immense value in deconvolution of seismic traces, specially when these are nonstationary as in seismic data for marine, shallow, hard water-bottom environments. Motivated by these views, Surendra Prasad and coworkers considered it desirable to investigate the effectiveness of an adaptive deconvolution approach to seismic data. Three specific configurations, viz., the adaptive tapped delay line filter, the adaptive lattice filter and the adaptive Kalman filter identifier were chosen for the study. It turned out that all the three methods exhibited superior performance to the fixed structure predictor. In addition, the adaptive lattice filter, which has a faster convergence rate than the adaptive tapped delay line filter, also exhibited superior deconvolution performance. The adaptive Kalman filter identifier was found to be better than both the others, but is computationally more complex.

The other algorithms proposed by Surendra Prasad and coworkers includes one based on the generation of a minimal order innovations model, another based on a constant coefficient ARMA model, leading also to a recursive ARMA algorithm and a maximum a-posteriori probability (MAP) criterion based detection/estimation algorithm.

Array pattern synthesis and adaptive arrays

Several factors have resulted in the need for formulating and solving a variety of new problems in array processing, such as optimization of beam patterns for irregular array geometries (as in conformal and towed arrays, for example), imposition of constraints (like directions of pattern nulls and sidelobes, etc., to eliminate known sources of interference as, for example, self-noise of the propeller for a ship mounted sonar array), automatic steering of the nulls in directions of strong, unknown interfering sources like jammers, etc., and a high resolution analysis of the field via short arrays in order to distinguish objects with small angles of separation.

A specific problem arose out of the need for an adaptive algorithm for a 36 beam HF array. The challenge here was that some of the major signals from the

transducers that are normally required in the adaptive mode of operation could not be accessed. Surendra Prasad and coworkers proposed a new adaptive algorithm based on a weight perturbation approach, which potentially, could convert any conventional non-adaptive array into an adaptive one, through the use of some additional software, but using only the signals available from the nonadaptive array.

Realizing the need for a broad minimum of the array response in certain applications (as needed for example, in channels with angular spreading, caused by multipath) to suppress some undesirable sources, a simple and elegant theory was developed for a family of such patterns, which could be easily realized via a linear array. The ideas suggested here were also shown to be applicable for the realization of an adaptive array, when the direction of the desired signal is known with some uncertainty. Later, somewhat in the same view a new class of array optimization problems were formulated, in which one seeks to optimize the response in a specified angular sector. The optimization of the array patterns were shown to be related to the well known prolate-spheroidal functions.

Surendra Prasad and coworkers also proposed a geometrical formulation for the problem of placing nulls in given directions, for arrays of arbitrary shapes. This is a simple geometric method (called the method of alternating orthogonal projections) for the iterative solution of this synthesis problem. Later this work was generalized further by developing a new class of array synthesis techniques, whereby the array pattern is optimised in some desirable sense (like low sidelobe level or beamwidth) subject to some linear and nonlinear constraints say, for obtaining nulls and sidelobes in certain prescribed directions. The novel techniques introduced here were used to obtain useful optimum designs having a low equiripple sidelobe behaviour, while yielding the prescribed nulls, etc., for the class of circular and arc arrays for the first time, for applications in sonar beamforming.

High resolution bearing and spectrum estimation

A major breakthrough in array processing took place in the late seventies, when Schmidtt and Reddi addressed the problem of bearing estimation of closely spaced multiple emitters from a rank deficient array covariance matrix. They showed via a geometric-algebraic approach, that the space spanned by the columns of the covariance matrix can be decomposed into two orthogonal

subspaces, viz., that spanned by the array manifold (comprised of the steering vectors of the sources whose bearing is sought) and that spanned by noise. This decomposition led him to the celebrated algorithm known by the name of MUSIC (MUltiple SIgnal Classification), which under high SNR conditions, is capable of yielding unlimited resolution.

Since the original publication of the MUSIC algorithm, a lot of interest has been generated in making it more useful from a number of different points of view, such as making it applicable to a larger class of problems than those originally addressed and making it computationally efficient. Surendra Prasad and coworkers got interested in some related problems that arise typically in a towed array system.

In the original MUSIC algorithm, the noise covariance matrix is generally assumed to be known, except for a scaling factor. This, however, is not warranted in practice, being generally an unknown entity. Surendra Prasad and coworkers suggested, therefore, the use of a transform based covariance differencing approach, in which, the subspace analysis is done on an appropriately constructed difference matrix, such that it eliminates the need for knowing this matrix. This approach was shown to be useful for a number of other problems as well, such as the estimation of time of arrivals of superimposed wavelets and the estimation of pole locations of a system function from measured transient response data, when the additive noise is nonwhite and unknown. Later, a method for identifying the signal and noise subspaces was obtained, without the use of the eigendecomposition and involving only simple householder transformations. This led to a significant increase in the computational efficiency of MUSIC for this class of problems.

Another related problem is concerned with the effect of multipath propagation on the high resolution bearing estimation algorithms. Surendra Prasad and coworkers have proposed a modified spatial smoothing algorithm, which improves upon the previously proposed technique, by reducing the loss in the array aperture inherent in spatial smoothing. The new technique, by virtue of its application of smoothing in both the forward and backward directions, makes more efficient use of the aperture. Later, an approach for the identification of the coherency structure of the sources based on this smoothing technique was also developed and it was shown that by looking at the ranks of a sequence of

smoothed covariance matrices, one can determine the source coherency structure in an efficient manner.

Sonar signal processing

Over the years, Surendra Prasad and coworkers have been motivated to look into several important problems concerning the active and passive sonar signal processing. The problem of time-delay estimation has attracted a great deal of attention in recent years. The accurate estimation of time delay between signal wavefronts arriving from a source at two or more geographically separated sensors is very important for passive sonar methods of source localization. They investigated the effect of medium scattering (such as occurring in acoustic propagation of the oceans), due to its practical significance. They showed that there exists an optimal separation of the sensors, for which the performance of both the range and bearing estimates based on time delay estimates is optimum, and also provided a method for calculating this optimal separation.

More recently, investigations into various aspects of towed array signal processing were taken up, with a view to help in the indigenous efforts being made to develop towed array systems in the country. Some of the problems that arise specially in the signal processing of towed arrays include, (i) distortion of the array shape in an unknown manner due to the hydrodynamical forces of the ocean and the motion of the towing vessel, (ii) presence of a type of a high wavenumber noise caused by the turbulence around the array, called flow noise, and (iii) loss of spatial coherence of the signal over the length of the array due to multipath. All these effects cause loss in signal detectability, as well as in the accuracy of bearing estimation. Surendra Prasad and coworkers have suggested some algorithms for the estimation of the array shape for the purpose of accurate beamforming. A general technique for the study of the spatial coherence loss across the array aperture for a specified velocity profile in the ocean was also developed, and its effect analysed on the performance loss of the conventional and optimal array processors. Reduction of flow noise has been investigated via the use of special signal processing techniques, whereby each element of the array is realised as a cluster of sensors.

Statistical modeling and adaptive signal processing

In many applications concerning time-series analysis and stochastic signal processing (as in the deconvolution problem discussed earlier), one of the

fundamental issues of interest is that of modeling a given stochastic sequence. This requires finite parameterization of the infinite autocorrelation of a given time series. The autoregressive moving average (ARMA) models are an important class of such parsimonious approximants. The literature is rich with a host of techniques for the identification of ARMA models, most of which, unfortunately, are either too complex or yield only a suboptimal solution. This is essentially due to the nonlinearity of the identification problem.

In some very recently published work Surendra Prasad and coworkers have attempted to explore the structure and properties of an ARMA process in depth, starting from first principles. By regarding the random variables as vectors in a Hilbert space, some interesting and useful results have been obtained concerning the nature of multiple-step ahead predictors of a time series. In the course of these investigations, an entirely new representation for these processes is obtained, called by them as a predictor space representation (PSR), which has a number of useful and interesting properties. Unlike the parameter space associated with the conventional ARMA representation, that associated with this representation is a linear one, which helps in obtaining a new optimal recursive procedure for the estimation of ARMA parameters and solving the so-called ARMA filtering problem.

More recently, the problem of multi-channel ARMA modelling has been taken up for investigation. In this work a periodic scalar representation of a multichannel ARMA process is proposed and its properties studied. This representation is shown to be useful in obtaining the ARMA parameters via an algorithm which is amenable to parallel processing on a (pipelined) multiprocessor architecture. The scalar representation is also used to obtain powerful least squares system identification and modelling algorithms, which are order recursive in both AR and MA orders, and which can be implemented on a pipelined architecture.

A very recent trend in statistical signal processing is the use of higher-order-statistics (HOS) for obtaining solutions to non-linear system problems. Surendra Prasad and coworkers have obtained HOS based high resolution estimation of quadratically coupled frequency components in a signal due to nonlinear interactions. These algorithms, besides being algebraically elegant counterparts of the second order MUSIC and ESPRIT algorithms, are of potential

use in studying nonlinear interactions in EEG signals and a variety of vibration systems.

Digital communications again: miscellaneous aspects

The problem of mitigating intersymbol interference when associated with non-Gaussian noise is more difficult than that considered in section IV. A basic theory for this subject is developed by considering several approaches for the design of what are called locally optimum receiver structures. Several alternative structures have been proposed, including among them, a decision feedback receiver, a composite-hypothesis testing MAP receiver and a maximum likelihood receiver. An efficient, though suboptimal, viterbialgorithm implementation of the maximum likelihood receiver was also obtained. Finally, Surendra Prasad and coworkers derived performance bounds for the nonlinear receivers for some typical non-Gaussian noise distributions and channels.

There has been a lot of interest, of late, in code division multiple access systems, such as in satellite and spread spectrum applications. For these applications, it is required to use binary sequences, which have a good (spiky) auto-correlation function, small cross-correlation values with codes of other users in the system and which must be difficult to decipher from a partial knowledge of the sequence for the purpose of secrecy. Some of the well known sequences having the first two of these properties are Gold sequences, Kasami sequences, etc. Unfortunately, these are not good sequences from the point of view of communication secrecy, since they are known to have a very small equivalent linear span, which is a measure of the ease with which these can be completely determined from a partial knowledge of the sequence.

Surendra Prasad and coworkers have obtained some new results in the design of such binary cipher sequences with good autocorrelation function for cryptographic applications, i.e., which simultaneously have a large value for the equivalent linear span. Later, using a nonlinear construction procedure based on interleaved m-sequences, another class of sequences were obtained which have good auto- and cross-correlation properties over the set, and also have a large value of linear complexity, thus making them difficult to break.

Current research and future plans

Current research activities include, among others, speech and image processing, higher order statistical signal processing and adaptive signal processing. Besides,

there is a lot of emphasis on application of theories to develop practical systems and provide new solutions to current technological problems, specially in communications and telematics. The modest efforts reported here have been possible due, in no mean measure, to contributions from a large number of wonderful colleagues and students.

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Vidyeswaran Rajaraman

Rajaraman's early research was in analog computation. He designed and constructed a non-linear function generator for an electronic differential analyser and explored other methods of developing non-linear units to solve non-linear differential equations.

Rajaraman changed his area of research to adaptive control system when he went to the University of Wisconsin for his doctoral work. He studied the properties of model reference adaptive control systems. The main contribution was the design of a parameter perturbation adaptive control system. He proposed the concept of a parameter servo to explain the parameter tracking capability of his system and evolved a theory to explain the observed experimental behaviour of the adaptive system[1].

On his return to India Rajaraman switched his area of research to computer science. He started exploring methodology of specifying complex decision logic, which occur in designing information systems. The main issues explored by him and his research students were in formulating complex logic as decision tables and their conversion to efficient computer programs. Significant contributions were the conversion of extended entry decision tables, to storage efficient programs[2] and a novel application of information theory to obtain near time optimal computer program[3]. Hitherto no definitive work had been done on detecting logical errors in decision table programs at compile time. This is of great practical interest as most error detectors at compile time detect only syntax errors and not errors in logic. For a class of decision tables it was shown that it is possible to detect logical errors at compile time. The novel idea was to convert the logical error detection problem to one of finding whether a set of linear integer inequalities has a feasible solution. Simple methods of finding the existence of feasible solution for the type of simple inequalities which occur in a

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programing context were proposed[4-6]. This work has found a place in text books and also in an invited article by the author[7].

Rajaraman was convinced that in a new discipline such as computer science in which very few researchers were working in India, it was essential to develop a school which is not narrow but investigates a wide range of topics. He thus guided doctoral students also in the area of memory design[8] data bases[9] and process control algorithms[10], while at the Indian Institute of Technology, Kanpur.

Rajaraman's work on dynamic memories showed how such memories can be used as associative memories[8] and also as first-in-first-out memories[11].

Rajaraman shifted to the Indian Institute of Science, Bangalore in 1982. This was the beginning of his interest in parallel computer architecture and applications. He was interested in building low cost parallel computers which could be used as test beds to explore issues in architectural design, programming environment, task allocation, performance evaluation, fault tolerance, etc. An important decision taken was to use IBM PC motherboards as the computing nodes. A high speed, bi-directional full duplex, byte wide link that can be plugged into personal computers was designed by him and his group[12]. This link enforces a first-in-first-out discipline in hardware without CPU overhead. A[16] processor hypercube was developed using Intel 80386 based motherboards and these FIFO links. A full software environment was built which supports writing parallel programs in Fortran, C, Pascal and Prolog, either under MSDOS or UNIX operating system.

A dimension-independent programming methodology allows development of parallel programs for hypercubes of any dimension. As the link is a low cost device, it would permit any engineering college which has a number of 80386 based personal computers to build parallel computers at a low cost as a teaching aid to teach parallel programming. The technology developed has been transferred to a small scale industry, which has sold many units to engineering colleges.

Another architectural approach was to design a bus-based message passing parallel machine. Using parallel buses for message passing had not been explored earlier and the group working with Rajaraman designed a machine christened Broadcast Bus Multicomputer System and showed that it is an efficient machine for a class of applications and can exhibit good speedup.

Apart from designing machines it is important to devise methods to solve important applications in parallel. In a series of articles Rajaraman and his

students studied solving partial differential equations and ordinary differential equations in parallel. A parallel predictor-corrector algorithm was proposed and a method was devised to maximise the interval of stability of the method. Appropriate architecture was proposed for solving non-linear partial differential equations, it was simulated and its efficiency was established.

Another major issue in parallel computers is the mapping of a program represented as a task graph on to the computer, in such a way that the total execution time of the program is minimized. The mapping problem should exploit any structure inherent in the task graph. In a series of papers Rajaraman and his students proposed parallelism measures of task graphs which were better than those in the literature, obtained tighter upper and lower bounds for computation time of programs on multiprocessors and gave some heuristics for assigning tasks to processors in a multiprocessor system.

Another direction of investigation was on the efficient execution of functional programs on parallel computers. Hitherto functional programs were evaluated either eagerly or lazily. In eager evaluation, functions were evaluated as soon as they could be evaluated, whereas in lazy evaluation execution was delayed and carried out only when necessary. There was a proposal on a via media execution model called speculative evaluation, in which functions which have a high probability of being evaluated are evaluated if free processors are available. In a paper, the question, when to evaluate speculatively was examined and a definitive result was presented on this issue[13].

Rajaraman's other interest has been in the application of artificial intelligence. The Department of Biotechnology of the Government of India wanted a data base of Indian biotechnologists working all over the world to be created and updated regularly. Earlier it had been done manually. Rajaraman proposed a method of scanning computer readable tapes of articles published in International journals, patents, etc., and detecting whether the author's name is of Indian origin. The problem was challenging as there is no algorithm which could recognize a string of characters as an Indian name. It was hypothesised that humans recognize names by vocalizing them. Based on this it was decided to use rules in Sanskrit, which allow only certain combinations of phonemes. An expert system was developed to recognize names based on this theory. It succeeded[14] very well in correctly identifying Sanskrit based Indian names with a margin of error less than 5%. This system was used very effectively in creating a data base as required.

Another issue which has not been well understood in artificial intelligence literature is how to quantify intelligence. The general problem is intractable. It was, however, proposed[15] that a vector measure would be appropriate for a certain class of problems. These problems are in a limited domain and called a Question-Answer System, in which a human subject is to identify an object or a personality by asking a series of questions. The model was proposed and intelligence measures were computed. This is a pioneering effort in this area and is expected to open a new area of investigation.

Another major contribution of Rajaraman has been the writing of lucid text books in computer science. He was the first in India to write a book on Fortran Programming which has been read by almost every scientist and engineer in India who started programming in the 1970s. This book has gone through three editions and 27 printings in the last twentyfive years. Besides this, he has written a dozen books among which are Cobol Programming, Computer Oriented Numerical methods, Computer Design, Information Systems Design, Parallel Computers, Pascal Programming and Supercomputers. These text books are widely used by students in India and has contributed to the spread of computer education in India.

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Arcot Ramachandran

Heat transfer is a branch of the broad field of engineering sciences encompassing solid mechanics, fluid mechanics and thermodynamics that came to be recognized as essential links in the knowledge that enables scientific principles to be adapted to yield technological devices for human development. The science of heat transfer concerns analysis of systems that exchange energy by virtue of temperature differences, while the technology of heat transfer deals with the thermal design, development and fabrication of such systems. It is no exaggeration that there is hardly a branch of technology that does not involve, directly or indirectly, temperature inequality and, therefore, heat transfer–be it in mechanical, electrical, electronic, chemical, metallurgical or aerospace engineering discipline. It was only in the late 40's and early 50's that the vital importance of this subject gave a quantum push to research in developed countries. During this time, very little work was being done in this field in India, since there were hardly any graduate programmes in engineering, leave alone in the special area of heat transfer. Against this background Ramachandran joined as the first faculty member of the newly established graduate programme in Mechanical Engineering at the Indian Institute of Science, Bangalore, in 1950 on his return from USA, where he obtained his doctorate in heat transfer under the late Max Jocob and George A Hawkins. It was a challenge and an opportunity.

During the next 17 years, Ramachandran was engaged in the task of building a school of research in heat transfer which attracted a number of visiting scholars and professors. Since India was just embarking on a major industrialization programme and concentrating on heavy basic industries during the second plan period, such as steel plants and foundry-forge units, it was felt that applied research in heat transfer should be directed towards practical systems

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in production technology. Accordingly, a major programme was initiated in the graduate division of foundry engineering on the study of mechanical properties, thermal properties and solidification of castings. The effects of many variables, such as mould ratio, chills, mould materials, the composition of alloys and the moulding methods on the thermal characteristics and thereby the mechanical properties of castings were investigated[1-4].

Another important area of heat transfer research activity during this period was thermal power plants. Use of lignite for power generation, pool-boiling heat transfer, combustion stabilization, high temperature properties of metals in the design of modern power plants and the thermal design of heat exchangers were some of the problems investigated[5-7]. On the basic research side, a major effort was undertaken in the area of thermophysical properties of metals and non-metals, gases and vapours, including refrigerants[8-10]. Fundamental problems of industrial significance in convective heat transfer, such as the influence of vibration, thermal entry length effects in concentric annuli, and hydrodynamics in circular and non-circular ducts were studied[11-12]. Work on these topics initiated in India for the first time during this period continues to be of topical importance even at the international level. The school of heat transfer research had a multiplier effect in the past two decades through its graduates and scholars continuing research in this field at their own institutions.

After taking over as the Director of Indian Institute of Technology (IIT), Madras, in 1967, Ramachandran gave a major thrust to research there by encouraging basic and applied research in all fields of science and engineering. In particular, in the area of heat transfer, refrigeration and air conditioning a new school of research was established under his direction. In the later half of the 60's, the results of the green revolution were becoming evident as were the effects of enhanced power generation and electronic industry. It was, therefore, essential that problems of heat transfer related to food products, such as refrigeration, freeze-drying and drying be investigated. It was also important for a tropical country like India that indigenous expertise be developed in research competence in the field of air-conditioning. Further, the sources of energy for thermal power generation in the short and medium ranges were likely to be coal and nuclear. Research was, therefore, launched into the latest technologies for coal utilization, such as fluidized bed combustion and heat transter and cooling of electrical machinery. The research school also initiated work on cooling of electric devices,

an area of great importance in view of the impending electronic revolution in the country.

In the area of food products, heat and mass transfer characteristics of food products in air cooling, storing and freeze-drying were investigated. Several analytical and experimental studies were undertaken to obtain charts which could be used in practice for predicting time-temperature characteristics during precooling and preserving of food products[12-14]. Work on heat transfer in and combustion of coal, in particular, lignite, using the technology based on atmospheric fluidized bed process was initiated in 1971. Fundamental hydrodynamic and heat transfer were investigated analytically as well as experimentally and the problem of development of a fluidized bed boiler with optimum tube-bundle internals was taken up under Ramachandran's guidance to investigate the thermal design of large turbogenerators. This problem is of great industrial importance in view of the trend in the power industry to go in for large-sized thermal units of 500 MW and above. Since the thermal design of the generator is invariably the limiting factor in the attainment of self-reliance in this field, a pioneering effort was undertaken in 1971 and through research collaboration with the BHEL, R & D continued over subsequent years. Cooling of electronic equipment was another new area of research initiated during 1971-73 at IIT, Madras. Revolutionary developments in micro-miniaturization of electronic equipment in the entertainment, communications and defence industries called for new, innovative and effective methods of transferring dissipated energy in the electronic devices to maintain the system within strict temperature limits, thus ensuring reliable performance. Natural, evaporative and cryogenic cooling techniques have been and continue to be investigated at the school of research, IIT, Madras.

After Ramachandran assumed charge as Secretary in the Department of Science and Technology (DST), Government of India, in 1973, a research and development programme in energy was initiated under his supervision, particularly in the solar, thermal and photovoltaic and other renewable energy sources. Basic and applied research on the exploitation of applied research on the exploitation of new and renewable sources of energy has been given great push in the country during the past decade. In collaboration with BARC and BHEL, DST initiated a major programme on power generation through the magneto-

hydrodynamic process, resulting in the commissioning of the 5 MW pilot magnetohydrodynamic power plant in Tiruchi in 1985.

Ramachandran has been an Under-Secretary General of the United Nations and Executive Director of United Nations Centre for Human settlements—UNCHS (Habitat). At the centre, several energy-related projects have been implemented under his overall guidance. They include: energy requirements and energy conservation in human settlements, land use in relation to solar energy, passive heating and cooling systems in human settlements, solar energy design data for use by architects, and energy generation utilizing urban waste.

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Viswanatha Ramamurti

The major contribution is in the field of stress analysis and vibrations related to mechanical engineering. This includes both analytical and experimental investigations. The activity covers practical units like fan impellers, fabricated gears, cement mills, kilns, circuit brakers, space frames, bus ducts, bus bodies, rail bogies and pressure vessels.

Research activity in the area of static analysis addresses the complexities associated with large size problems. Optimization of bandwidth, efficient algorithm for solving large size simultaneous equations and experimental investigation at site to verify the findings of the units investigated are areas of activity. The practical units investigated include heavy duty gear box casings, machine tools like shapers, hydraulic presses, plate bending rolls, press brakes, multilayered pressure vessels and centrifugal baskets. Particular mention should be made of cement mill stress analysis. This investigation covers determination of dynamic pressure on the mill at site, methodology (semi-analytic approach to three-dimensional problems) for determining the dynamic stresses on the mill, verifying them at site, failure analysis and parametric study.

The area of eigen value analysis addresses the problems associated with industrial units like fan blades, rocket launchers, boiler frames, machine foundations and steam turbine shafts. Use of simultaneous iteration scheme for in-core and out-core analysis, Lanczos scheme for reduced labour have been implemented. The analytical investigation has been accompanied by experimental investigation at site.

Study of cyclic symmetric structures has been a major area of activity. Applications cover a wide range, such as impellers, gear wheels, turbo chargers, gear hobbers and turbine blades and discs. The entire investigation is grouped under three heads: (i) static and steady state analysis of cyclic symmetric objects

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subjected to cyclic symmetric loading, (ii) static and steady state analysis of cyclic symmetric objects subjected to general loading, (iii) eigen value problem associated with cyclic symmetric objects. Since the conventional method of analysis involves enormous core and labour, optimization of these two aspects has been of main concern.

The ideal finite element used for solving problems under this category are triangular shell elements with six degrees of freedom at each node, and eight node brick elements with three degrees of freedom at each node. In both the cases, the stiffness and mass matrices formulated in Cartesian coordinates are to be transformed to the polar form, resulting in displacements along radial, circumferential and axial directions. The shell element adequately models problems associated with bladed discs, fabricated gear wheels and pressure vessels. Brick elements suit units of comparable geometry, like milling cutters, gear hobbers, drills, reamers, bevel, helical and spur gears. The research work covers analysis using skyline approach for incore solution, submatrices elimination scheme for out-of-core solution, and Ritz-Wilson approach for dynamic analysis. The analysis includes the study of the role of complex numbers in the formulation and solution of both static and dynamic problems. Research work covers experimental investigation also.

Another area of concern has been the dynamic analysis of mechanical elements. This includes both transient and random inputs. Use of modal superposition technique, time integration scheme, and power spectral density and transfer function has helped in solving industrial problems. Study includes response of bus bodies subjected to random input from road undulations, response of bus ducts and circuit brakers owing to earthquake, response of rocket launchers and sharp shooters due to shock loads. The input, in some cases, has been verified in the field. Transient response of disk blade assembly during run up and brake shoe assembly during braking are interesting problems investigated. Investigations concerning Stockbridge dampers on transmission lines and torsional vibration dampers on internal combustion engines highlight the role of damping in dynamic response.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Guruvayur Subramaniam Ramaswamy

Overview of research achievements

Ramaswamy's major contributions by way of research, development and innovation during the past 35 years have been in the area of long span roofs and floors which provide large unobstructed spaces uncluttered by columns for auditoria, conference halls, indoor sports stadia, cathedrals, industrial sheds and institutional buildings. The research carried out has led to the development of new or improved materials, new structural forms, simplified methods of structural analysis and appreciable savings in critical materials, such as cement and steel which are often in short supply. The underlying objective of all of his research activities has been the development of structural forms and techniques that result in the use of a minimum of materials to maximum structural advantage. These considerations led him to concentrate his research efforts on two major areas: (i) concrete thin shells, and (ii) reinforced and prestressed concrete, which offer considerable scope for developing cost-effective structural schemes for long spans. The research carried out in these areas has led to the publications of two internationally known and widely used text and reference books.

Varied experience made it possible for Ramaswamy to bridge the yawning gulf that often separates research from practice by incorporating the findings of his research in some of the pace-setting structures that he designed as a consultant. Another major achievement was the establishment of the Structural Engineering Research Centre, a national laboratory of CSIR of which he was the founder director.

Contributions of thin shells

Although Ramaswamy has made several original contributions to the theory of cylindrical shells[1,2], conoids[3] and prestressed hyperboloids[4], and shared the Gammon prize for developing design principles for the first-ever folded plates

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built to be continuous over three spans[5], his most significant contribution is the development of a new form of shell which has come to be known as the funicular shell. The motivation for developing this new form of shell was rooted in necessity. In the late 1950s, the country was faced with an unprecedented shortage of cement and steel. Just at that time, the Ministry of Defence had plans to build 1400 houses for army personnel at Ambala. He was asked to come up with a roofing element that can be made *sans* cement *sans* steel. He thought of some form of shell roof. But all shell forms, then known, have tension regions and they cannot be cast without steel reinforcement. Lime-surkhi mortar that he proposed to use to save cement is fairly strong in compression, but it has hardly any tensile strength. Obviously, he had to find a shell form which will develop only pure compression when submitted to the action of loads. He was led to the conclusion that to achieve this, the normal sequence followed in the design of shells must be reversed. Instead of assuming an arbitrary geometry and topology to start with, one must assume a desired state of stress, say uniform compression, and proceed to find the appropriate shape. This led to the funicular form. The first papers on this new form of shell were published in 1958[6-8].

A simple casting technique using a hessian fabric sagging under the weight of wet surkhi mortar to let the shell 'cast itself' to the appropriate shape was also devised and patented[9] to permit the mass manufacture of such shells even in the remote villages of India using unskilled labour. The shape of the funicular shell is governed by Poisson's differential equation and the casting technique just described amounts to letting gravity solve the differential equation. The best examples of funicular brick shells built in India are those designed by Ramaswamy and his colleagues for the National Institute of Design at Ahmedabad and the Structural Engineering Research Centre at Madras. These were cast on accurately cut forms conforming to the funicular shape. Other notable examples are the shell roof over the municipal auditorium at Kanpur and the Catholic Cathedral at Lucknow. Shells were also used for an unprecedented application at Madras Port for the heavy duty floor of a loading platform for carrying heavy industrial loading.

Contributions to reinforced and prestressed concrete

Ramaswamy's research efforts in the area of prestressed concrete have been aimed at gaining a better understanding of the twilight zone between fully prestressed and reinforced concrete, so that an integrated approach to the design of reinforced concrete and prestressed concrete becomes possible by regarding them as the two ends of the spectrum of structural concrete. This approach has

been presented in his book[12] and a paper read at the FIP Congress held in New York[13].

In a joint paper[14] with his coworkers, Ramaswamy conclusively demonstrated that a saving of 33% in the steel used as concrete reinforcement aggregating to a total of 0.45 million tonnes of steel per annum can be effected if reinforced concrete structures are designed on the basis of ultimate strength and high yield strength deformed bars replace mild steel as reinforcement. This paper had a far-reaching impact on the building industry. It ushered in the changeover from elastic to ultimate strength design; it also generated a demand for high strength deformed bars. To meet this demand, one of his colleagues and he developed and patented a high strength deformed bar. Manufactured and marketed under the trade name of TISCON by TISCO, it replaced imported TORSTEEL technology.

Recent directions of research

Ramaswamy is involved in the following research activities:

(i) *Compiling a monograph on funicular shells :* The aim of this project is to document his contributions and the published work of others, which being widely scattered in numerous publications, are not easily accessible. He also intends to initiate some additional studies, the findings of which will also find a place in the monograph. These additional research investigations will generate a lot of thesis material. Hence, they are best pursued in an academic environment in collaboration with young research colleagues.

(ii) *Development criteria for the design of tall structures submitted to the action of wind loads :* Because of the current trend towards superthermal power stations, a large number of very tall chimneys and cooling towers ranging in height from 100 to 250 m are either under construction or are on the drawing boards. Such structures can be designed economically only if the wind velocities, and hence the wind pressure for which they are to be designed, are prescribed rationally. A stochastic approach based on the analysis of data available on wind velocities must replace the current deterministic codes and computer-based methods of structural analysis need to be developed. This programme can be best pursued in an institution in collaboration with young research colleagues.

(iii) *Development of inflatable forms for casting concrete shells :* The cost of formwork constitutes a major proportion of the total cost of a concrete shell roof. An appreciable reduction in cost can be realized if inflatable forms can be developed and used. The scope of the research planned includes the formulation of design principles and development of practical details.

(iv) *Development of designs and the planning of a pilot project involving the building of a solar chimney :* Combining the principles of a greenhouse, the windmill and a chimney, the solar chimney offers a cost-effective means of tapping solar energy and converting it into electrical energy in a country such as India. The main component involved being a tall chimney, the problems involved in developing an economically viable unit are in the realm of structural engineering. This project is best pursued in an institutional environment, where inter-disciplinary inputs and interaction are possible.

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Srinivasa Ranganathan

Introduction

Our ability to design materials with an attractive combination of properties has been vastly enhanced in scope by the introduction of metastable microstructures. The recent spate of discoveries relating to metallic glasses, quasicrystals and nanostructures has generated an exciting renaissance in structural metallurgy. Ranganathan and coworker's research activity has been concerned with the synthesis and analysis of metastable microstructures. A strong thread of applied geometric insights underpins their work.

While the phase diagrams offer useful guidelines for the development of alloys, these imply certain restrictions. These limitations can be evaded by preparing metastable alloys far away from equilibrium by using a variety of techniques. Rapid solidification of a number of aluminium, titanium and iron base alloys has been accomplished, using melt spinning, laser glazing and spray forming. Mechanical alloying has emerged as a powerful rival to rapid solidification in the production of metastable microstructures. Many binary and ternary titanium alloys have been mechanically alloyed to produce extension of solid solutions, nanocrystals and metallic glasses.

Interfaces

A pioneering contribution to a theory for the atomic configuration at grain boundaries was reported in a 1964 publication in *Acta Metallurgica*, which became a citation classic. This analysis of the geometry of grain boundaries led to a generating function for coincidence site lattices known as the Ranganathan generating function and has entered textbooks.

Early work revolved around the field-ion microscope with atomic resolution capabilities. Extensive use of geometric analysis and computer

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simulation was made to solve the problem of contrast from perfect crystals as well as dislocations, stacking faults and domain boundaries.

The role of grain boundaries and interfaces in transformations is an area of great import. The possibility that the transformation from one close-packed structure to another in cobalt alloys occurs by the dissociation of grain boundary dislocations has been examined. It was demonstrated that this could not serve as a general mechanism.

Ordering in crystalline alloys

Ordering and clustering are opposing tendencies in alloys. Nevertheless they can both occur by a continuous mode. During an investigation of ordering in Ni-Mo and Ni-W alloys, the nature of short range order and the occurrence of metastable phases received attention. The complicated sequence of transformation in Ni_3Mo has been followed to establish the time-temperature transformation curve. The strengthening arising from ordering in these alloys has been conclusively traced to domain size. The ageing temperature played an important role in the mode of transformation in Ni-20% W alloy. At relatively high temperatures, a heterogeneous mode prevailed. Perpendicular twins formed and new domains were nucleated near grain boundaries. At lower temperatures, homogeneous nucleation occurred leading to a mosaic structure. Thus it is possible to vary the microstructure in the ordered alloy by suitable changes in the heat treatment schedule.

Spinodal decomposition in Co-Ti alloy has been studied. Though matrix and precipitate structures are the same as those encountered in the nickel base super-alloys, the transformation occurs by a different route. The kinetics of coarsening of the modulations, the development of particles, the loss of coherency and the generation of misfit dislocations were all monitored to yield a wealth of information, which enabled the correlation of microstructure with attained strength values. Fe-Ge alloys, where both ordering and clustering can proceed together, have been studied and compared with Fe-Si alloys.

Noncrystalline alloys

Metallic glasses possess attractive mechanical, magnetic and chemical properties. The thermal and chemical stability of amorphous alloys has been investigated. Crystallisation behaviour of a wide variety of glasses, e.g. Vitrovac 0040 ($Fe_{40}Ni_{40}B_{20}$) Metglas 2826 ($Fe_{40}Ni_{40}P_{14}B_6$) and Metglas 2826 MB ($Fe_{40}Ni_{38}Mo_4B_{18}$) has been followed using differential scanning calorimetry and transmission electron microscopy. Nucleation of crystals and their subsequent

growth were studied from the kinetic and mechanistic point of view. A comparison among the three modes of crystallization, namely primary, eutectoid and polymorphic crystallization was formulated. A new relationship between activation energies for different processes was postulated. A new and as yet unexplained observation is the increase in interlamellar spacing with decreasing temperature. The electrochemical corrosion of Vitrovac 0040 as a function of chloride and sulphate concentration has been investigated using potentiodynamic studies in the glassy and crystalline states.

Recent work has been concerned with the formation and stability of aluminium base metallic glasses in Al-Y-Ni, Al-Y-Cu and Al-Cu-V alloys. The crystallization sequence of metallic glasses in these systems has been established.

Extensive investigations on the formation of metallic glasses in titanium base alloys by mechanical alloying has been carried out. Glass forming ranges in binary Ti-Ni, Ti-Cu, Ti-Al and ternary Ti-Ni-Cu and Ti-Ni-Al systems were established. The concept of milling maps was introduced based on two energy parameters, namely, the impact energy of the ball and the total energy of milling. The precise conditions necessary for metallic glass formation by mechanical alloying can be predicted in terms of these two energies from these milling maps. The principle of predicting glass forming ranges from free energy—composition diagrams was extended to ternary alloys.

Quasicrystalline phases

Aperiodic tilings were discovered by R Penrose as an exercise in mathematical recreations. Their possible existence was the dream of physicists such as A L McKay. They have become a metallurgical reality, thanks to the discovery of quasicrystals (QC) in rapidly solidified Al-Mn alloys by D Shechtman and coworkers in November 1984. The most fascinating aspect of these materials is the generation of sharp electron diffraction patterns.

Significant discoveries relating to primitive and face centred icosahedral three-dimensional QC, decagonal two-dimensional QC, trigonal one-dimensional QC have been made. In addition, the rational approximant crystalline structures with startling similarity to QC were identified. An enhanced understanding of twinning in the context of QC has been achieved.

Following the pioneering discovery of quasicrystals in Mg-Al-Zn alloys by P Ramachandra Rao and G V S Sastry, a new icosahedral quasicrystalline phase in Mg-Al-Zn-Cu alloy was discovered. A measurement of the quasilattice constant enabled V Elser to distinguish between two classes of primitive

icosahedral quasicrystals. This work has been extended to show that the two different classes of quasicrystals map two different regions, when a dimensionless QC constant is plotted agains *e/a* ratio. This observation strengthens the possibility that these phases can be treated as a Hume-Rothery phase. The growth of QC phases poses some interesting problems. The first observation that they could grow in a facetted form was made. In the case of Al-Mn alloys, the shape was identified as a pentagonal dodecahedron. Extensive observations of twinning of quasicrystals were reported.

The first experimental evidence of the possibility of an ordering reaction in a QC was presented. The occurrence of diffuse intensities along odd parity directions was interpreted as arising from an ordering reaction. Subsequently, a stable ternary Al-Cu-Fe quasicrystal, displaying perfect face-centred ordering, was discovered by Japanese scientists. All the important zone-axis electron diffraction patterns from this phase have been assembled together in a map.

The vacancy ordered phases observed in the aluminium-transition metal systems can be treated as one-dimensional quasiperiodic structure at the limit based on the Fibonacci sequence. Different ordered structures correspond to different levels of truncation of this sequence.

A degeneration of the reciprocal space with respect to the icosahedral symmetry has been shown in Al-Mn-Si, Mg-Zn-Al alloys. Specifically a 3/2 rational approximant crystal has been identified in Mg-Zn-Al alloys. The shift of the spots from the ideal positions delineating quasicrystallinity has been quantified. Two rational approximants to the decagonal phase based on Al-Mn-Ni and Al-Mn-Cu phases were identified.

A spin-off of research on quasicrystals has been the discovery by L Bendersky and coworkers of a new irrational twinning mode; whereby the lattice is twinned but the motif maintains orientational bond order across the twin interfaces. This concept has been extended to several systems and a link with the early work on coincidence site lattices was established.

Nanostructured materials

Nanostructured materials offer tempting new combination of properties. The fraction of atoms residing at grain boundaries begins to equal those within the bulk. While a number of sophisticated techniques is available for the synthesis of nanostructured materials, rapid solidification, mechanical alloying and devitrification offer elegant and relatively inexpensive routes.

The formation of nanocrystalline phases in binary Ti-Ni, Ti-Cu, Ti-Al and ternary Ti-Ni-Cu and Ti-Ni-Al alloys by mechanical alloying has been studied. Particles in the size range of 20 nm were produced. Devitrification of the initially formed amorphous phase into intermetallic compounds has been observed in the case of Ti-Ni-Al alloy. A nanosize Ti_2Ni structure has been detected. Further study is expected to increase our understanding of the structure and properties of grain boundaries.

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Patcha Ramachandra Rao

Casting of metals is an ancient art. However, the scientific principles underlying solidification of metals and alloys have been developed and understood only in the last few decades. It is, therefore, not surprising that experiments aimed at cooling liquid metals at the phenomenal rates of 10^{6}-10^{10} K s^{-1} were conceived and carried out only in the early sixties of this century. The pioneering effort in this area was due to Pol Duwez of the California Institute of Technology, Pasadena, USA. Duwez and his coworkers demonstrated that solidification at such large cooling rates can result in the formation of metastable solid solutions and intermediate phases and yield metallic glasses. These results gave considerable impetus to alloy development and opened up a new and fascinating field for physical metallurgists. The group at the Department of metallurgical Engineering, Banaras Hindu University, was quick in realizing the importance of such studies and Ramachandra Rao pioneered these studies at Varanasi.

Rapid solidification of alloys is achieved through the production of thin (< 40 µm) layers of liquid metal over highly conducting substrates. In the early years of development, the objective was attained by shooting a small quantity of liquid alloy, with the aid of a shock tube, on to a ski-slope substrate. The technique has come to be known as the gun technique. Alternatively, in the piston-and-anvil technique, a freely falling droplet is caught between a stationary anvil and a fast moving piston. Ramachandra Rao combined these two techniques to yield large (7-8 cm diam) discs of rapidly solidified alloys for physical and mechanical property determinations. Working in association with the group at the University of Sussex, Brighton, UK, Ramachandra Rao was able to exploit the high thermal conductivity of diamond at sub-zero temperatures and generated the highest cooling rates known to date. The collaborative research also demonstrated, for the first time, the usefulness of lasers in generating metastable intermediate phases on the surface of irradiated alloys. The advent of the melt

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spinning technique has enabled the production and technological exploitation of metallic glass tapes. The development of the planar glow casting technique at Allied Chemicals, USA, has made the production of broad tapes a reality. These techniques have also been established at Varanasi under a nationally coordinated project on metallic glasses for the development of Fe-B and Fe-Si-B alloys for use in power transformers.

Early years of rapid solidification studies were devoted to a study of aluminium alloys. The choice of aluminium was dictated by the abundance of this metal in the country. Ramachandra Rao and his group have investigated several binary systems based on aluminium and having bismuth, cadmium, copper, germanium, indium, lead, nickel, platinum and silver. The studies showed that extension of solid solubility limits of these solutes can be achieved and that several new metastable intermediate phases can form in these alloys. In a few cases, glass formation was also detected. besides aluminium alloys, a few alloys based on noble metals were also studied and characterized. The thermal stability of the rapidly solidified alloys and their ageing behaviour also received attention and the decomposition schemes of many of these alloys were drawn up. Among the results achieved, the production of grain sizes of the order of 100 Å, formation of metastable prototype phases, such as $Al_3\ Cu_2$, novel vacancy ordered phases, detection of twinned dendrites, etc., deserve mention.

Experience gained through the study of rapidly solidified alloys very soon demonstrated that a factor of paramount importance is the degree of undercooling achieved. Attempts were, therefore, made to undercool 30-50 g quantities of alloys by the well known glass-slap technique. Towards this end, silver-germanium and cadmium-zinc alloys were selected and treated and used in making window glass and $ZnCl_2$ glass slaps, respectively. It was demonstrated that undercooling gives metastable solid solution in both these alloys, the contents of alloying elements in solution being comparable or superior to those observed in rapid solidification experiments. The glass-slag technique is not universal in its applicability, owing to difficulties in selecting non-reactive glass for every alloy system studied. To overcome part of the problem, the group adapted the technique wherein liquid droplets are entrapped in the solid metal matrix by holding in the mushy, i.e., liquid + solid region and repeatedly cycling them between the holding and room temperatures. Spectacular successes were achieved by this route by way of producing metastable phases in aluminium-germanium alloys and glassy phases in magnesium-zinc alloys. Such studies and still underway on several monotectic alloys. The results obtained by the group on undercooling have

formed the basis of the materials science experiment conducted in space by Squadron Leader Rakesh Sharma during the Indo-Soviet Joint Space Mission of April 1984.

The many faceted results obtained through rapid solidification and undercooling require a sound explanation in terms of thermodynamics and energetics. Ramachandra Rao and coworkers have striven hard to develop such models. The earliest such attempt showed that a direct correlation exists between the peaks in partial excess entropy plots against composition and metastable phase formation. Subsequent studies were aimed at establishing the existence of clusters in the liquid state by fitting the observed free energy and enthaply values to the regular associated solution model for compound forming melts. The method was extended to include explanations for glass forming tendency as well.

Glass formation was also predicted through several alternative models based on the calculation of either the volume changes that accompany mixing in the liquid state or the hole concentration in the liquid. The former approach predicted the composition ranges suitable for glass formation, while the latter was able to predict the critical cooling rate for glass formation, the magnitude of property changes at glass transition, the viscous behaviour of undercooled melts and the temperature dependence of the free energy of the undercooled melt with respect to the solid state. It can also predict the ideal Rauzmann glass transition temperature with remarkable accuracy from the heat capacity and entropy differences between the liquid and solid phases at the melting temperature.

Towards the end of 1984, a remarkable observation was made in rapidly solidified aluminium-manganese alloys by the group at the National Bureau of Standards, USA. They detected crystals with five-fold rotational symmetry, which is incompatible with translational symmetry. These crystals, since christened quasi-crystals, have generated great enthusiasm among solid state physicists and physical metallurgists and almost all the initial results were obtained on aluminium-manganese alloys. Ramachandra Rao and Sastry showed that such crystals can be anticipated on the basis of the crystal structure of equilibrium compounds; they synthesized quasi-crystals by rapidly solidifying Al-Mg-Zn alloy. Several other similar alloys have since been studied by the Varanasi group and their results have provided many more alloys for investigation.

Continuing on the these of aperiodic crystals, Ramachandra Rao and coworkers have also looked at the two-dimentionally aperiodic Penrose tilings. A novel algorithim was developed to yield, without fail, perfect penrose vertices and

tilings of predesignated tile sizes. The approach has also enabled the derivation of the structure factor and diffraction intensities of such tilings.

Rapid solidification is fast growing into a technology. Several products of this young area of research have already found industrial and commercial applications. Currently Ramachandra Rao and his group at Jamshedpur are engaged in the study of spray forming as a tool for the production of near net shapes.

After joining the National Metallurgical Laboratory Ramachandra Rao has turned his attention to the production of nanocrystalline materials. In this direction, powders of the permanent magnetic materials $Nd_2 Fe_{14} B$ and high purity alumina have been produced and characterised. Several novel aspect of synthesis and raw materials recycling have been incorporated into the methods developed. Other current areas of interest include industrial waste utilisation and metal-matrix composites.

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Paranandi Venkata Suryanarayana Rao

India's first computer

Rao started his professional career with the design and development of TIFRAC, India's first computer at the Tata Institute of Fundamental Research. This activity was started from scratch, by him and others who, being first generation computer scientists, did not have any previous training, experience or exposure to work in this area. He designed and built the arithmetic unit and the cathode ray display system for TIFRAC. These incorporated several innovative features (carry bypass logic for fast addition, design of high speed glitch-free shift counters, etc.). The carry bypass/ripple carry feature is incorporated into arithmetic logic units of present day PC's.

In his PhD thesis project, Rao introduced, in the 1950's, a new scheme for line-segment display of alphanumeric characters; this improved legibility and clarity and reduced memory requirements. This was the first time that line segments were used for character display. The idea subsequently became very popular for high quality CRT displays, graphic plotters, non-impact printers, etc.

Second computer

After returning from the University of Illinois (where Rao worked on the design of the high speed ILLIAC II computer), Rao was involved with hardware developmental activity at the Tata Institute of Fundamental Research. His responsibilities during this period included establishing a digital system laboratory involving 15-20 scientists and engineers to undertake various system design and implementation tasks. OLDAP, an on-line data processor, was designed and built by this group.

The machine, the first of its kind in India, was built using locally made entertainment grade components. Building reliability and speed into a large

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system using slow, non-switching junction transistors and point contact diodes meant for the entertainment industry, was a challenging task which was successfully accomplished by him and his team. The system (i) demonstrated the feasibility of designing large digital systems using mainly Indian components, (ii) highlighted the utility of online computers for real applications in India, and (iii) gave rise to a number of innovative ideas in the area of digital circuits and system design, e.g. a fast circuit switching logic module which utilizes slow transistors and junction diodes not intended for such applications; a simple peak detector readout circuit for magnetic disk units; and a highly regulated very low voltage power supply with failsafe short-circuit protection and reliable power supply interlock controls.

The impact of this work on the national scene has thus been quite significant on all three counts. The design of this computer was futuristic. Many of the system design features incorporated here (such as flexible register assignment, a variety of addressing modes, two-address instruction scheme, etc.) became available only several years later in commercial machines offered by leading manufacturers.

Large systems for major national needs

As a consequence of the competence so established, the group under Rao's leadership was assigned the total responsibility for two national projects for realizing (a) a command and control system, and (b) a switching system for voice, teleprinter, facsimile and digital data. These, the largest of their kind, were launched by the Government of India as inter-institutional projects, since the requisite know-how did not exist in any single institution.

The task forces formed to realize these systems consisted of about 80 engineers, scientists and senior officers from the Tata Institute of Fundamental Research, Government of India and private sector laboratories and industry, as well as the Indian Army and Air Force. Additional work assigned to these institutions were executed by them at their own respective locations, also under Rao's supervision.

The work involved system design, system engineering, hardware design, development of systems and applications software, finalization of production prototypes, ruggedization, environmental and other testing and establishing a production line for the products.

The development projects and the systems developed were the largest of their kind ever to be attempted in India in the area of electronics. The systems

designed and developed by this group successfully underwent the full range of defence specification tests as well as hardware and software performance tests under operational conditions of temperature, humidity, shock vibration, transportation, etc. Knowhow for these systems was then successfully transferred to the Electronics Corporation of India. A large number of the systems have been manufactured by ECIL, supplied to the user; they are currently under active use along the borders of India. A group that worked under him (and M V Pitke) on one of the projects formed the nucleus of the CDOT unit in Bangalore and are currently under operational use.

Speech and signal processing

Rao initiated activity in the area of speech synthesis and recognition by computer in India at the Tata Institute of Fundamental Research. Several important and original contributions were made by him and his coworkers in the area of speech research.

Rao proposed and implemented (with R B Thosar) a novel scheme for computer synthesis of speech which is flexible, simple and elegant: grouping phonemes into equivalence classes and sub-classes (on the basis of similarity of context influence on neighbours) and defining phoneme concatenation rules for these classes and sub-classes instead of for an individual phoneme. His conjecture that such a classification would be closely parallel to the one based on articulatory similarities, turned out to be correct and represented a significant insight.

Rao's scheme for speech recognition (with Thosar) utilizes information contained in formant transitions for improved recognition scores. Also, it is synthesis-based: it employs transition segments synthesized on the spot rather than prestored templates for comparison with the test sample. In a clever way, this prevents variations in the steady segment properties from interfering with recognition of the transition segments, and yields a significant improvement in the recognition scores. In this scheme, recognition based on steady state segments is followed by that using transition segments. As variations in vowel parameters will affect CV/VC transitions, use of prestored templates for recognition is undesirable; transition templates are, therefore, synthesized on the spot using vowel parameter values extracted from the sample under recognition. This makes recognition of CV/VC transitions insensitive to vowel formant variability. He also extended this scheme to connected speech (with K K Paliwal). Recognition scores are 52% (using steady state segments only) and 64% (using transitions also), illustrating the validity of this approach.

Rao's work shed light on an important aspect of speech perception by humans. Formant transitions which are important cues for perception of stop consonants are, to a certain extent, also influenced by contextual effects due to non-immediate neighbours. This work has established that these effects are not important for human speech perception. The human listener considers the speech signal only two phonemes at a time and is concerned only with context effects of adjacent phonemes on each other. This result is of relevance for synthesis and recognition of speech by machines.

A cross-linguistic study performed in this area by Rao (and K M N Menon) threw light on another interesting aspect of the human speech perception mechanism. He and his collaborators have also been responsible for a number of other original ideas in the areas of speech signal processing, pitch extraction and so on.

Knowledge based computing system technology

Work done on speech processing by Rao's group over several years set the stage for this group being nominated as a nodal centre for the knowledge based computing systems project funded by the Department of Electronics (Government of India) and the United Nations Development Program. The computers systems and communications group under Rao took up the responsibility for implementing a VOICE (Voice Oriented Interactive Computing Environment) system as part of this responsibility. This system used an innovative feature based approach for speech recognition and implemented a number of demonstration projects which established the relevance and importance of speech technology in India. These included a railway reservation enquiry system in Hindi, a computer aided instruction system and a telephone based information retrieval system. These were successfully demonstrated to the UNDP evaluation team.

Due to the involvement in speech recognition, Rao got interested in natural language processing, since higher level language knowledge is essential for robust recognition of speech. Rao (with Nandini Bondale) developed a so called blank slate language processor, which not only disambiguates between the options offered by the acoustic level recogniser, but is in addition able even to supply correct words in place of those which have been wrongly recognised at the acoustic level. It acquires knowledge about the structure of a language by exposure to it, and is therefore useful in a variety of task environments involving man-machine transaction.

Rao (and Nandini) used this language processor for evolving a model of the grammar of a child at various stages of acquiring a language. The other applications are in machine translation and machine understanding of speech, in well defined task domains.

Due to close similarity with speech, Rao got interested in cursive script and developed an approach for synthesis of cursive script from individual characters and script characters from more basic elements called shape vectors. This approach is based on a target shape driven system for the writing hand, where conscious feedback or active control is restricted mainly to ensuring conformity with the very broad features of the shapes of the characters being written; finer details are controlled mainly by constraints regarding continuity of shape and movement, achieved as an intermediate curve level sensory motor feedback function without conscious higher level brain control. This model inspired a recognition approach using parameters which retain information regarding the broad shapes of script characters, and permit the finer shape details to be ignored/filtered out. These features are robust enough to permit quantisation on a coarse grid, so that size, slant and other writer specific variations in these shapes can be viewed as noise and filtered out. The recognition scheme, consequently, is based on a representation of the work prototypes in the lexicon as an archetypal or canonic form. The test words are also parametrized and the parameter values are quantized. This desensitizes the representation to the distortions that corrupt the character shapes, by essentially filtering them out as noise too complex. Consequently, the system operates without elaborating training of the type required by conventional pattern recognisers.

Policy planning and implementation for technology development

In addition to work in the areas of computer systems and speech research, Rao was concerned with and played an active part in the evolution of policy and planning for technology development in electronics in general and in the area of computers in particular.

As a member of the Technology Development Council and Chairman of the Working Group on Computer Systems and Applications, Department of Electronics, Government of India, it was Rao's responsibility to identify and promote well chosen research activity to be financed by government in selected thrust areas, identify suitable projects for funding and monitor their progress.

As Chairman of the Panel on Mini Computers of the Government of India, Rao was responsible for a comprehensive analysis of the need for mini-

computers, evolving a policy approach for establishing and licensing of manufacturing and suggesting an overall framework for the growth of research and development in this field.

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Palle Rama Rao

Rama Rao's research contributions are principally in two areas of physical metallurgy: (i) X-ray diffraction study of structural imperfections in metallic materials; and (ii) correlation of mechanical behaviour (tensile, creep, fatigue and fracture characteristics) with the microstructure of metals and alloys.

Rao's X-ray studies on imperfect metallic structures had the three-fold objective of innovating methods for the analysis of X-ray diffuse scattering for eliciting information on parameters (domain size and lattice strain), reflecting dislocation (line defect) densities, and distribution and the type and extent of stacking faults (planar defects). His pioneering work has been on close-packed structures [e.g., double hexagonal close-packed (DHCP)] hitherto not studied and on potentially significant systems belonging to the well-known face centred cubic (FCC) and hexagonal close-packed (HCP) structures.

In the area of new methods of analysis of X-ray line broadening, Rao's contributions include development of a simple method of analysis utilizing integral breadths; formulation of a modified Fourier technique requiring only single diffraction lines where practical limitations preclude the use of multiple orders of X-ray reflections, as required in the well-known Warren-Averbach method; suggestion of a new procedure based on elastic anisotropy for the separation of stacking fault and domain size components when Warren-Averbach Fourier transforms are used for the analysis of X-ray diffraction effects in body-centred cubic (BCC) structures; and advancing of an interpretation of X-ray line shifts due to stacking faults from purely geometrical considerations.

Rao and coworkers postulated, for the first time, possible fault configurations in DHCP crystals. X-ray diffraction effects were subsequently evaluated by one of his colleagues and the experimental work on a DHCP Au-Cd-In alloy provided comprehensive evidence for all the predicted X-ray diffraction

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effects, leading to complete evaluation of seven fault probabilities. Development of crystal structures with a larger number of layers in the stacking sequence, akin to polytypism, was also observed for the first time on splat-quenching the DHCP Au-Cd-In alloy from the liquid state.

Several significantly original experimental results have been derived by Rao in the course of X-ray measurements on a variety of metals and alloys belonging to the FCC and HCP classes. The observation and separation of extrinsic stacking fault contribution in Pd, systematic elucidation of the effects of electron concentration and solute-solvent valence difference on propensity to faulting in a series of binary alloys with the discovery of the heaviest faulting ever noted for alloy systems, observation of a strain-induced FCC $\rightarrow$ HCP transformation, striking evidence for d-band contribution to stacking fault energy, and the novel extension of some of these concepts with new measurements on FCC ternary alloys, binary HCP alloys and more complex materials, studies on the effect of thermal and mechanical treatments on faulting, and the first measurements of faulting in liquisol-quenched materials, are illustrative of Rao's endeavours in this field.

Significant contributions of Rao with regard to the correlation of mechanical properties with microstructure concern high strain fatigue at ambient and elevated temperatures, power-law as well as viscous creep, creep fracture, Portevin-Le Chatelier effect and solid particle erosion, besides novel studies pertaining to tensile deformation and fracture characteristics of carefully chosen alloys. Deformation as well as fracture mechanism maps, based on experimental observations, have been constructed for metals and alloys of technological importance.

Remarkable effects of grain boundary mobility on high strain fatigue (HSF) characteristics at elevated temperatures were shown by Rao's group from their work on Al and Zn. The effect of tensile prestrain on HSF of an indigenously produced Nb stabilized high strength low alloy steel, the impact of high strain rate sensitivity index of flow stress on HSF of a superplastic bronze, the influence of varying microstructure on HSF of Concorde Al Alloy RR 58 at ambient as well as elevated temperatures, the effects of ferrite-martensite microstructural morphology and the volume fraction of martensite on HSF of dual phase steel are striking research results on important new alloys. The observation of two-stage cyclic work hardening and its bearing on two-slope Coffin-Manson behaviour in dual phase steel treated to develop inhomogeneous microstructures are noteworthy new results in the field of high strain fatigue. That the magnitude of

cyclic strain hardening exponent is related to the extent of deviation from Masing behaviour is another new result of importance to low cycle fatigue.

Notable aspects of the work of Rao and coworkers on power-law creep and creep fracture pertain to elucidation of the effects of polycrystal grain size on high temperature strength, creep rate, creep ductility and creep rupture life. The role of dislocation substructure induced by thermomechanical treatment, and the complex effects that arise due to the interplay of the same with creep-induced development of dislocation substructures has been analysed in great detail in an Al-Mn alloy specially suited to this work. The work on the role of grain boundary migration led to the discovery of the occurrence, during creep, of the so-called diamond grain morphology, a surprising microstructural development. In another investigation, the presence of an anodic surface oxide was shown to strongly inhibit the creep of even polycrystalline metals. By the use of the scanning electron microscope, details hitherto unnoticed in the transgranular creep fracture of Al were unravelled, while showing that although intergranular failure was conspicuously absent during creep, intergranular cracking occurred during fatigue of Al at high temperatures. Rao and coworkers have also carried out studies on the low stress viscous creep of cobalt, titanium, zirconium and zircaloy and have obtained interesting results. In the course of this work, experimental evidence has been obtained, for the first time, for the occurrence of Harper Dorn creep at temperatures as low as 0.5 T_m, where T_m is the absolute melting temperature; this was until recently considered to occur only at temperatures close to the melting point. For the first time, experimental creep mechanism maps covering viscous as well as power-law creep mechanisms have been constructed for alpha-titanium, alpha-zirconium and beta-cobalt.

The relationship of microstructure and internal structural features that can be revealed only with high resolution techniques, with mechanical properties, constitutes one of the foundations of the new science of engineering materials. However, the only mechanical property which has been researched in this light so far, to such an extent that not only control of such a property in the existing alloys can be exercised but also design of new engineering alloys can be attempted, is the yield strength. There are a number of other properties of great significance to mechanical performance where similar understanding is yet to emerge. This is the major concern of Rao's current work. One instance of notable work in this context relates to the understanding of the role of stacking fault energy in the mechanical damage caused by solid particle impingement utilizing a series of copper-base solid solutions. In another instance, the subtle influence of

microstructure on fracture toughness has been elucidated in terms of grain boundary chemistry and transformation products resulting from heat treatments of an ultrahigh strength maraging steel. The microstructural effects on fracture processes in aircraft high temperature titanium alloys have been studied and fracture mechanism maps have been constructed for titanium and a series of its alloys. A major effort has been presently undertaken to understand the fundamental role of solute additions in determining the resistance to failure in metallic systems.

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Vellenki Umapathi Reddy

Reddy's research covers data windows, fast algorithms, finite wordlength effects, spectral estimation, adaptive algorithms, direction-of-arrival (DOA) estimation, beamforming, smoothing techniques and neural networks.

Data windows : Data windows play an important role in digital signal processing. Here, Reddy developed a set of windows from raised-cosine pulse. In particular, the sum-cosine window, which yields 6 dB improvement in the first sidelobe gain with no loss in the main lobe width and maximum sidelobe gain compared to that of the near optimum zeroth-order Bessel window, is significant. The distinct feature of these windows is their very simple form.

Fast algorithms : Finite-duration impulse response filters are important, as they are easy to implement and robust to finite wordlength effects. In applications where data rates are high, one resorts to implementation of these filters in transform domain. In this context, Reddy (along with his student) developed algorithms for computing fast convolutions using rectangular transforms and developed complex-rectangular transforms for this purpose. Also, they proposed implementation of Winograd's algorithm in modular arithmetic to realize error-free convolutions.

Finite wordlength effects : Study of finite wordlength effects is important in digital signal processing. Reddy analyzed the fixed-point error performance of fast Fourier transform (FFT) algorithms and along with his associates developed the first prototype 32-point cascade FFT processor. This work was of substantial help to LRDE (the premier Radar centre of DRDO) in its development of a contemporary pulse-doppler radar for the detection of low-flying targets. He along with Samson gave the first fixed-point error analysis of recursive ladder (or lattice) type adaptive algorithms.

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Spectral estimation and adaptive algorithms : Reddy has made significant contributions in these areas. An adaptive filter configuration known as the adaptive line enhancer (ALE) was proposed by Widrow *et al.* (in 1975) for extracting a sinusoidal signal buried in broadband noise. Reddy was the first to propose an optimal form of the ALE by showing that an optimum value exists for the so-called decorrelation parameter (previously always taken to be unity). Along with his student, he extended this to the case of multiple sinusoids and also devised an iterative method for estimating the optimal value. The ALE with the optimal choice of the decorrelation parameter yields superior spectral estimates.

Pisarenko was perhaps the first to propose an eigenvector-based solution (in 1973) to the classical problem of estimating sinusoidal signals in additive white noise. Since then several efforts were made to find adaptive implementation of this method. Reddy's solution to this problem (a least-squares type algorithm) was the most efficient. He also extended this algorithm to the 2-D case. Most recently, he (along with his associates) derived an improved version of his earlier least-squares type algorithm and analyzed its convergence rigorously.

Among the linear prediction based methods of spectral estimation, modified forward-backward linear prediction (MFBLP) and modified backward linear prediction (MBLP) proved very effective in estimating the frequencies of undamped and damped sinusoids, respectively, when the data size is short (they attracted a lot of attention by the spectral estimation research community). It was experimentally shown by the authors of MFBLP that the predictor order $M = 3N/4$, where N denotes the number of data samples, yields best frequency estimation performance. These techniques (MFBLP and MBLP) implicitly assume the knowledge of the number of sinusoids (undamped or damped as the case may be). In practice, however, this information is not known *a priori*, and hence, one has to extract this information from the given data. Reddy (along with his students) has made significant contributions here. First, he developed a subspace based analysis to explain why for the predictor order $M = 3N/4$, the performance of the MFBLP method is the best. Second, he proposed some improvements to the MFBLP method and the improved version performs better than the MFBLP at lower SNR's and lower predictor orders. Third, based on the information theoretic approach to model selection, he developed detection criteria for detecting the number of sinusoids (undamped/damped) from the given data.

DOA estimation : Subspace based (or eigenstructure based methods of DOA (direction-of-arrival) estimation such as MUSIC (multiple signal classification) and minimum norm (MNORM) have received a lot of attention

since their discovery. These algorithms provide high resolution and also yield unbiased estimates of DOA's asymptotically. In the original development of these algorithms, following assumptions were implicit: (i) signals impinging on the array are not fully correlated and the data available for processing is unlimited, and (ii) exact characterization of the array in terms of its geometry and sensor response is known *a priori*. In practice, however, it may not be possible to meet these conditions and as a result the performance of these algorithms degrades. Reddy (along with his students and associates) has made several original contributions in this area.

Reddy has analyzed the effect of spatial smoothing (uniformly weighted subarray covariance averaging) on the performance of the MUSIC algorithm in the presence of partially and fully correlated signals, and shown that smoothing improves the DOA estimation performance. This study assumed the knowledge of exact array characterization.

Exact characterization of the array in terms of its geometry and sensor gain and phase may not be possible because of measurement errors, changes in the surrounding environment and sensor misplacement, etc. Hence, it is of interest to know how sensitive these methods (MUSIC and MNORM) are to deviations from the assumed array manifold. Reddy's work in this context (along with his students) first addressed the sensitivity of MUSIC and MNORM methods to sensor gain and phase errors assuming infinite data. Next, he analyzed the performance of these methods in the presence of both finite data and sensor errors. Specifically, the expressions for the mean-squared error (MSE) in the DOA estimates were derived. This analysis explicitly brought out that MUSIC (and its root version) is less sensitive compared to the MNORM (and its root version). These results provide guidelines for choosing the data size and calibration accuracy for a specified level of performance. Considering an inverse problem, he proposed a technique to estimate the sensor gain and phase assuming that DOA's of some of the impinging signals are known. This finds applications in calibrating the array manifold periodically.

Beamforming : Capon's optimum least-squares beamformer, known also as the minimum variance (MV) beamformer, received a lot of attention since its development in 1969. In this beamformer, sensor outputs are combined by suitably weighting the signals so that the desired directional signal passes to the output without distortion while the interference signals are rejected to the maximum extent. Correlation among the impinging signals (caused due to mutipath or smart jammers) can severely damage the performance of the

beamformer. Not only does the beamformer fail to put deep nulls in the direction of the interferences, but also the desired signal can be partially or fully cancelled. Reddy first analyzed the signal cancellation and interference rejection performance of the MV beamformer in the presence of arbitrarily correlated interferences. Then, he showed quantitatively how spatial smoothing progressively decorrelates the impinging signals, thereby improving the signal cancellation and interference rejection performance of the beamformer. The analysis is asymptotic, i.e., the data size assumed is infinite. This analysis, which was first developed for stationary arrays, was later extended to moving arrays. Motivated by the above study, he (along with his associates) proposed new approaches to optimum beamforming in the presence of signal correlated interferences that completely eliminate the signal cancellation.

Reddy's most recent work on this subject is the finite data analysis of the MV beamformer in the presence of arbitrarily correlated interferences. This analysis explicitly brings out the trade-off between the data size and the number of sensors in the array. It shows that in addition to decorrelating the impinging signals, smoothing also reduces the perturbation effects caused by finite data. It has also revealed that satisfactory performance can be obtained with only a single snapshot if sufficient number of sensors are available. These results serve as useful guidelines in practical applications.

Smoothing techniques : The spatial smoothing, suggested in the context of both DOA estimation and beamforming, suffers from a reduction in the effective aperture of the array. To avoid this reduction in the aperture and at the same time provide the advantages of spatial smoothing, several authors have proposed redundancy averaging as an alternative. Reddy (along with his student) analyzed this technique and showed that it destroys the eigenstructure of the underlying signal. Specifically, the resulting signal subspace fills up the whole space and also the resulting array covariance matrix is not guaranteed to be non-negative definite. As a result, the resulting DOA estimates are biased.

Reformulating the spatial smoothing as a generalized weighted smoothing problem, Reddy developed a procedure to obtain a set of optimum weights which gives minimum mean-squared error (MSE) in the DOA estimates. Since computation of the optimum weights requires full knowledge of the scenario, which is not available *a priori*, a practical approach to estimate these weights from the given data has been suggested.

Neural networks : In the eigenstructure based spectral estimation methods, one has to seek the noise (or signal) subspace. Pisarenko's harmonic retrieval

method was perhaps the first in this class. The basic step in this method is the computation of the eigenvector corresponding to the minimum eigenvalue of the auto-correlation matrix of the underlying data. Recasting a known constrained minimization formulation for obtaining this eigenvector into the neural network (NN) framework, Reddy (along with his student) proposed and analyzed a new approach. The NN is of feedback type, with the neurons having sigmoidal activation function. The approach is quite general, in that it can be applied to estimate the minimum eigenvector of a general symmetric matrix which is not indefinite. Combining this with an inflation technique, he developed an adaptive approach to estimate some or all of the orthogonal eigenvectors of the given matrix. Limiting the desired eigenvectors to those of noise subspace (or signal subspace), the method can be straightaway used in adaptive implementation of the subspace based high resolution techniques. As a complementary problem, he also developed a NN approach for simultaneously estimating all or some of the orthogonal eigenvectors of a symmetric non-indefinite matrix corresponding to its repeated minimum eigenvalue.

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Gitindra Saran Sanyal

Sanyal has been engaged mainly in research in the field of electro-magnetics and its application to microwave and antenna engineering over the past few decades.

Sanyal's initial research work dealt with the estimation of ferromagnetic permeability in the microwave frequency band. He devised an experimental set-up for its measurement. Later, he developed the conformal transformation for the determination of amplification factor of triode having elliptic cross-section. This was followed by extensive investigations into aperture type antennas. While studying the radiation pattern from the open end of X-band rectangular waveguide, he analysed the effect of cutting the waveguide with different inclinations towards its axis. A discussion on this work, which has been widely referred to, was included in the Book "*Antenna engineering*" by Jasik.

In the course of further investigations, Sanyal made useful contributions to the field of slot antennas by evaluating their self and mutual impedances in the wall of rectangular waveguide. This yielded dependence of radiation pattern and impedance characteristics of slots on the field distribution in the aperture plane of slots, indicating excellent correlation between theoretical and experimental results.

Sanyal also took up investigations regarding the sectoral horn antenna with curved aperture. The radiation pattern for both concave and convex cuts on the face of E plane and H plane sectoral horns was formulated and almost simultaneously, studies on periodic structures were conducted. In continuation of these, he found ω-β relation for sinusoidally modulated rectangular waveguide and assessed the dispersion characteristic and the condition for matching. He further made a formulation for periodic structures consisting of X-band rectangular waveguide, periodically loaded with thin posts. These studies showed excellent correlation between theoretical and experimental aspects.

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At the Indian Institute of Technology (IIT), Kharagpur, Sanyal established a new centre of research activities named Radar and Communication Centre (RCC). He was able to create and guide there a highly motivated research group on antenna and microwave engineering. This group undertook many project works in the field of radar and communication funded by the Ministry of Defence, Department of Electronics, ARDB and other organizations and made notable contributions.

As initiator of research work in the field of phased array antenna, Sanyal explored many new aspects of different types of phased arrays and their feeds. Many prototype phased arrays and phased array components were developed, which are available in the Microwave and Antenna Engineering Laboratory of IIT, Kharagpur. Investigations into different aspects of phased arrays were performed by researchers attached to the RCC and their results were published in reputed journals like *IEEE Transactions*. Along with the study of some new aspects of non-uniformly spaced array, impedance formulation was prepared using plane wave spectrum approach. This work found mention in a large number of publications, including journals like *IEEE Transactions*.

Sanyal has also carried out research on improvement in front-to-back lobe ratio of parabolic antenna by using shrouds and has succeeded in achieving positive results in this important aspect of antennas.

In 1979, Sanyal established the facility of research in the fields of fibre optics and fibre optics communication. He has organized several short-term courses and summer and winter schools on this topic in this area. In addition, he has been participating in the development of antenna systems for navigational aids and radar. His research activities have been highly appreciated and recognized by various agencies.

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Vallury Visweswara Subrahmanya Sarma

Early work

Sarma's PhD thesis topic was *Optimal control of systems with quadratic performance criteria*. The work reported in the thesis is broadly divided two parts: part 1 deals with optimal control of systems with quadratic performance criteria and part 2 with sensitivity studies of such systems. The problem of optimal control of a linear system is solved in the framework of Hilbert space. The method elegantly brings out the necessary and sufficient conditions and the equivalence of these conditions with the classical conjugate point conditions of calculus of variations is established. The relations with its dual problem, the Wiener-Kalman filtering problem are explored and solutions are obtained for the case of linear stochastic differential games, where each player has access only to noise corrupted measurements of states. A main result is concerning the study of performance sensitivity of linear optimal control systems to large parameter variations[1]. A method for reducing trajectory sensitivity has also been proposed.

Systems engineering

A significant portion of the work of Sarma is in the general area of systems engineering. The work started with the PhD thesis of Mansoor Alam (IISc, 1974) which looked at the problem of applying control theoretic models to the problem of machine maintenance. The models unified several issues such as deterioration of equipment with age, catastrophic failure, intermittent breakdowns and repairs, availability of repairmen and interaction of control and management problems[2-4].

This work provided the starting point for a significant study concerning operational effectiveness of fleets of trainer aircraft of the IAF. This work was supported by AR & DB. These researches led to formulation of cyclic queue and queuing network models for estimation of trainer aircraft at a flying-base, resource allocation between acquiring new aircraft and setting up of repair depots

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and policy evaluation for spares management[5-7]. A new method for aeroengine testing has been proposed[8].

Reliable computing

As part of the studies in airfleet reliability, it was observed that the reliability of a modern aircraft depends on the reliability of the on board computer. Sarma developed along with his PhD student A Pedar of the National Aeronautical Laboratory, Bangalore new methods for reliability analysis of aerospace computer systems using phased mission analysis and proposed new architectural schemes for aerospace computers with simultaneous consideration of performance and reliability issues[9-11]. This period also resulted in publication of the research monograph on the *Reliability of computer and control systems*[12].

Pattern recognition

The first notable contribution is to design schemes for identification of human beings based on their speech patterns[13]. The subsequent work in this period concerned with optimal design of decision tree classifiers and pattern recognition when feature measurement costs are considered[14]. Several studies on the use of fuzzy sets in pattern recognition were conducted[15].

Artificial intelligence

Sarma's research and development work during the period 1989-94 is concerned with *Studies on design of intelligent and knowledge-based systems*. His research in knowledge engineering is concerned with development of a new paradigm for knowledge-base construction called knowledge teaching. The use of education metaphor has helped the understanding of the knowledge acquisition bottleneck in expert system design.

Another area of his recent interest is the use of new tools based on influence diagrams for a variety of problems in pattern recognition system design and in developing intelligent decision support systems for project management. He has also started work on multi-sensor data fusion and battle field decision support in command and control. An expert system was developed for remote sensing data interpretation.

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Man Mohan Sharma

Gas-liquid reactions/reactors

New theories for complicated reaction systems have been developed and these have resolved many paradoxes. Linkages between theory and practice have been established; the classic work on absorption of carbon dioxide in amines and alkalis provided a rational basis for the design of industrial absorber-reactors.

New systems have been suggested which would conform to a particular regime of mass transfer with reaction and thereby enable the determination of transport coefficients as well as interfacial areas by chemical methods. Measurements of effective interfacial area and true mass transfer coefficients, in a variety of gas-liquid contactors, have been made. New strategies have been devised to obtain, with the same systems, values of true mass transfer coefficient and effective interfacial area.

Novel strategies have been suggested to increase the rates of fast gas-liquid reactions; these include the use of second liquid phase, emulsified with the original liquid phase, which shows much higher solubility for the solute, and the use of microemulsions.

Treatises on simultaneous absorption of two gases and description with reaction, including simultaneous absorption-desorption with reaction, have been published, along with experimental and theoretical work.

A novel example of desorption of an intermediate product, even though the reactions are instantaneous, has been brought out theoretically and confirmed experimentally.

The role of microphases in improving selectivity of the desired solute in simultaneous absorption of two gases has been clearly brought out.

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Rigorous procedures for the design of reactors have been suggested and these have been adopted in practice.

Liquid-liquid reactions

The chemical method of measurement of interfacial areas in liquid-liquid systems was pioneered. Many novel aspects of enhancement of fast and slow liquid-liquid reactions have been proposed and verified. In particular, the role of phase transfer catalysis, micellar catalysis, hydrotropy and small carbon particles has been brought out in an innovative way.

A novel room temperature process for the preparation of triaryl phosphates has been developed, which exploits phase transfer catalysis in an imaginative way and this process has been exploited industrially. The use of phase transfer catalysis in recovering phenolic substances from waste streams has been demonstrated and this was the first example of its kind.

Three-phase reactions

The effect of the presence of micron sized particles, smaller than the diffusion film thickness, in slurry reactors, has been clearly established. A new theory, which accounts for the dramatic enhancement in the specific rates of mass transfer, has been developed. Earlier, a new theory for situations where sparingly soluble fine particles are encountered in instantaneous reactions was developed, it has important applications in flue gas desulphurization. Solid-liquid reactions have been intensified through new strategies. The role of micron size bubbles in gas-liquid-solid reaction systems has been brought out and the beneficial effects have been stressed.

The role of Omega phase in markedly enhancing the rates of solid-liquid reactions, with phase transfer catalysts, has been brought out and examples of industrial importance have been cited. It is even more striking that, in some cases, phase transfer catalysts can change the course of reaction in solid-liquid systems.

Engineering analysis and design of gas-liquid and liquid-liquid contactors

The efficacy of co-current downflow packed columns, for irreversible reactions, has been brought out. Systematic studies on the performance characteristic of conventional as well as unconventional types of contactors have been made. New scale-up and design concepts have been suggested for a variety of contactors, notably bubble columns and mechanically agitated contactors; new strategies for operating such reactors have been suggested. Measurements of local values of heat transfer coefficients in bubble columns and mechanically agitated contactors have been made through an ingenious study of mass transfer coefficients. The

multiple circulation cell model has been developed for vertical (including sectionalised) and horizontal sparged reactors to predict axial mixing and correlate heat and mass transfer data on a rational basis. This was probably the first example of predicting backmixing in large industrial columns, on the basis of a rational semi-theoretical approach. The design of conical baffles for three-phase (gas-liquid-solid), sparged reactors has been worked out on a sound basis and backmixing characteristics of the solid phase have been assessed.

New separation methods

Separation of several close boiling acidic/basic mixtures by dissociation extraction have been accomplished. New regenerative methods have been developed. A new technique of dissociation extraction crystallization has been developed. Hydrotropic effects have been utilized to carry out separations of close boiling substances. Solid mixtures of close boiling substances have been separated in an ingenious way by using aqueous micellar solutions and microemulsions. Extractive distillation with a new class of solvents based on aqueous solutions of hydrotropes has been developed.

Ion exchange resins and clays as catalysts

Some novel aspects of the ion exchange resins as catalysts for alkylation of phenol and substituted phenols, dimerization of olefins, etc., have been brought out. The highly selective etherification of *p*-cresol, in the presence of 2, 6-xylenol, with isobutylene; selective etherification of β-naphthol in the presence of α-naphthol with isobutylene; selective alkylation with alphamethyl styrene of *m*-cresol, in the presence of *p*-cresol; selective etherification of ethanol, in the presence of isopropanol, with isobutylene; esterification of olefins with acetic acid, etc., are some specific examples of academic and industrial importance; such selective reactions also provide a basis for separation of close-boiling mixtures. The acetylation of diisobutylene and disoamylene with acetic anhydride has been successfully carried out. Clays have been used for selective alkylation and etherification reactions. These have been adopted in industrial practice.

The selective D-alkylation of phenol with cyclohexene has been realised with both ion exchange resins and clays as catalyst; the latter being more selective. Similarly, for aldol condensation of cyclohexanone acid activated clays have been found to be superior compared to cationic ion exchange resins.

The removal of formaldehyde, at low concentrations for aqueous solutions, through reaction with methanol to give methyllal has been accomplised with ion

exchange resins. Here distillation column reactor can be advantageously employed.

Recovery of chemicals from liquid waste streams

Novel methods have been developed to recover toxic chemicals from waste streams, including phenolic materials in alkaline systems and nitrobenzne sulphonic acid in aqueous solutions containing sulphuric acid. Adsorptive separations, based on activated carbons and polymeric adsorbents, have been used for difficult solutes like morpholine, pyridine, picolines, para-toluene sulphonic acid, etc. Thus liabilities have been converted into assets.

Contributions as a consultant

Novel processes have been successfully developed for speciality chemicals for pharmaceuticals and fine chemicals, for the first time in India, and these have resulted in an investment of over Rs 400 million.

Many ideas have led to substantial improvements in the existing plants, particularly sodium bicarbonate, soda ash, phenol, diacetone alcohol, alkyl phenols, etc. New strategies in recovering valuable chemicals from waste streams have been utilized; these include recovery of resorcinol from a waste dirty stream; recovery of fumaric acid from waste gases of phthalic anhydride plants, etc. Utilization of several by-product streams to value-added products has been successfully executed.

Solvent extraction has been used in a novel way to treat waste streams from a group of nitroaromatic plants.

Several new projects have been identified and these are being executed or have been executed with a total investment of nearly Rs 3000 million.

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Digvijai Singh

The flow-field in the clearance space of hydrodynamic and hydrostatic journal bearings and fluid seals, taking into account the complexities of configurations of these machine elements and also those arising out of constitutive behaviour of the fluid have been extensively studied by Singh. The former includes citron shapes with and without offsets, multilobe geometries, and tilting and rolling pad supports. The latter includes Newtonian and non-Newtonian fluids (effect of additives), micropolar fluids (particulate contamination) laminar and superlaminar flow, magnetohydrodynamic lubrication, elastohydrodynamic lubrication and also the more complex but more accurate piezothermoviscous behaviour of liquid lubricants. His work includes gas bearings (compressible fluids) used in very high speech application. His studies of hydrostatic bearings with restrictor compensation through a unified analysis lead to a very effective tool for optimal design of bearing-restrictor systems. The profile work of Singh in this area has been published in national and international journals, is widely referred to and has been used in industrial applications. In early 70's he was among the few first in India to use FEM to solve complex flow-fields in the clearance space of bearings and seals.

Singh's work in the area of dynamics of single track vehicles and tyre pavement interaction is important and significant. In 1984, as a follow up of his own doctoral work on dynamic stability of motorcycle (a study supported by a well known American firm), he carried out more realistic studies on several Indian vehicles and pneumatic tyres of various Indian makes. Over the years, the small group created and motivated by him diversified this study and several other vehicles were studied. This led to establishing a small vehicle laboratory at the University of Roorkee, which now has indigenously designed tyre testing facilities and facilities for the measurements of vehicle parameters and conducting road tests for the validation of models of vehicle dynamics. The Volkswagen

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Foundation has provided support for his small team to conduct a study in collaboration with the University of Stuttgart. During eighties great strides were made worldwide in the area of multibody dynamics and computer generation of equations of motion through coded formalisms. The current focus of this collaborative study is three-wheeled motorized vehicles, a class of vehicle very popular in India but not studied adequately, since it is not popular in the West or in Japan.

Singh's work on pneumatic tyres and tyre-pavement interaction model to predict the transient and steady state response to steering inputs are important, since the model can be effectively used in simulation of vehicle motion. The nonholonomic motion simulated by multi-body formalism has been employed to carryout parametric studies to arrive at optimum design of steering and vehicle configuration, which have need of great value to some Indian industries manufacturing two- and three-wheeled vehicles.

Singh has also done static and dynamic analysis of complex mechanical structures and continuums for leading Indian industries. These include chassis frames of double-decker buses, frames of motorscooters, bedplates for assembly of turbogenerator rotor laminations and dynamic tests of turbogenerators. These have been utilized by the industries.

Singh's earlier work in the area of welding engineering and welding physics was well recognized and was published in national and international journals. It includes studies on weld pool solidification, effect of welding parameters on molten metal transfer, spatter, heat affected zones (HAZ) and change in crystallographic structures correlating the mechanical properties. His work also includes analytical prediction and measurement of residual stresses in and around spot welds, this could be of interest to automobile and other industries. He has significantly contributed in identifying thrust areas in welding science for coordinated research.

Pavement measurement system (PMS) concepts have acquired great importance, since they determine the total transportation cost and affect the investment decisions. PMS can be of various degrees of complexity depending on the road network to which it is applied, the serviceability expected or desired, the traffic volumes the network carries and their projected levels and a number of other factors including climatic variables. The concept is new in India. Singh is coordinating a research group to develop PMS suitable for the Indian traffic conditions and applicable at local, regional and national levels. Since a very large amount of network data would be required which would be collected by a large

number of persons distributed all over the country, data collection and computer interface protocols are required together with properly developed and validated quality control and quality assurance filter programs. Singh's contributions may be useful and effective in the long run when PMS gets implemented at regional, state and national levels.

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Eleswarapu Chinna Subbarao

Subbarao started his professional career with a brilliant academic record in the production of ceramic sanitaryware and jars and after two years entered the research path. His major contributions have been summarized in the following.

Ferroelectrics

Domains : Within the field of materials science, Subbarao's first major contributions are in electrical and electronic ceramics, more specifically ferroelectrics. His PhD thesis on *Domain effects in barium titanate*, demonstrated clearly for the first time that ferroelectric domains get reoriented under the influence of mechanical stress. This is a direct consequence of the tetragonality of the polar state. The domain reorientations in this case were detected by changes in X-ray diffraction intensity of suitable planes, as also strain using strain gauges. The strain arises from the fact that polar axis (tetragonal C) is longer than the non-polar axes and the domain reorientation by 90° causes mechanical deformation. The domain switching process is a function of time at constant stress (anelastic behaviour). On removal of the applied stress, some of the strain is recovered as a function of time indicating partial domain reversal. It is well known that the application of a dc electric field causes domain alignment in the field direction (called poling) and that only partial domain reversal occurs on removal of the electric field, leaving the ferroelectric ceramics with a remnant polar character, leading to the poled ceramic exhibiting piezoelectric behaviour. The fact that domain reorientations do indeed take place under the influence of the mechanical stress and electric field is confirmed by the absence of changes in dimensions and X-ray intensities in the paraelectric state (above the Curie temperature) of the material. Many years later, with one of his students, V C S Prasad, this work was extended to another ferroelectric crystal, $KNbO_3$ (which is isomorphorous with $BaTiO_3$). The orthorhombic crystal undergoes permanent deformation under mechanical stress and this is due to 60° domain

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switching. The original shape of the crystal can be restored by applying stress in an appropriate direction. These early experiments on the bistable deformation associated with domain switching are forerunners of what has been classified as ferroelastic behaviour many years later.

Fine grain ceramics : Ferroelectric lead titanate undergoes abrupt lattice parameter changes at the Curie temperature, 490°C, which makes the ceramic to crumble on cooling from sintering temperature. Introduction of a small amount of Nb^{5+} in place of Ti^{4+} ion introduces vacancies and decreases grain size, so that dense, strong ceramic of $PbTiO_3$ can be obtained. Subbarao demonstrated this following his work on $BaTiO_3$, doped with Nb and Ta.

Morphotropic phase boundary: Morphotropic phase boundary in ferroelectric compositions based on $PbNb_2O_6$, discovered by Subbarao, has opened up a new family of optoelectronic materials with outstanding properties for a wide range of nonlinear optical applications. Subbarao *et al.* reported such morphotropic phase boundaries in $Pb(Nb, Ta)_2O_6$ and $(Pb, Ba) Nb_2O_6$ systems. The $(Pb, Ba)Nb_2O_6$ system is the parent of the technologically important systems such as $(Sr, Ba)Nb_2O_6$ for electro-optic applications.

Ferroelectric bismuth layer compounds: A landmark contribution of Subbarao to the field of ferroelectrics is his systematic work on the crystal chemistry, dielectric properties, phase transitions and crystallography of bismuth layer compounds, first studied by Aurivillius. They have a generic formula

$$(Bi_2O_2)^{2+} (Me_{m-1}R_mO_{3m+1})^{2-}$$

where Me = mono-, di- or trivalent ions or a mixture of them, R = Ti^{4+}, Nb^{5+}, Ta^{5+}, etc., singly or in combination and $m = 2, 3, 4$, etc.

The three variables, Me, R and m, give rise to a large number of compounds, many of which were found to be ferroelectric. Representative examples are $PbBi_2Nb_2O_9$ ($m = 2$, $T_c = 560$°C), $Bi_4Ti_3O_{12}$ ($m = 3$, $T_c = 675$°C), $PbBi_4Ti_4O_{15}$ ($m = 4$, $T_c = 400$°C). The crystal structure consists of one or more perovskite-like units sandwiched between two layers of Bi_2O_2. In addition to distinct compounds, complete solid solutions can be formed between isomorphous end members with a regular variation of Curie temperature. The Curie temperatures in this family range from over 900°C to less than room temperature. The recently discovered cuprate superconductors bear a structural similarity to this ferroelectric family.

Ionic conductors

Another area where Subbarao made significant contributions is ionic conductors—doped zirconia, doped thoria and beta alumina. Density and X-ray diffraction intensity measurements were utilised to establish the existence of anion vacancies in zirconia doped with CaO. The decrease in conductivity and increase in activation energy for conduction with increasing CaO content in the cubic phase field were explained in terms of steric hindrance to the movement of anions from one vacant site to the next. Annealing CaO rich zirconia solid solution at 1000°C leads to superstructure lines in the X-ray pattern and a lowered electrical conductivity, both of which are attributed to a disorder-order transformation on annealing. Defect structure and electrical conductivity studies have been extended to thoria systems doped with CaO and Y_2O_3 as well as the more complex ternary systems ZrO_2-Y_2O_3-$Nb_2(Ta_2)O_5$. In the ternary systems, introduction of Nb_2O_5 or Ta_2O_5 into ZrO_2-Y_2O_3 system annihilates some of the existing anion vacancies. These materials were characterized by measurement of electrical conductivity as a function of temperature, partial pressure of oxygen, composition as well as thermo-electric power. Zirconia and thoria systems possessing anion vacancies are useful as solid electrolytes in oxygen sensors, oxygen pumps, fuel cells, etc. On the other hand, sodium ions are located between spinel type layers of alumina in beta alumina and their transport across a membrane can be exploited for energy storage, as in a sodium-sulphur battery.

Phase transitions in zirconia

Zirconia (ZrO_2) undergoes the following transformations:

$$\text{monoclinic} \xrightarrow{1170°C} \text{tetragonal} \xrightarrow{2370°C} \text{cubic} \xrightarrow{2680°C} \text{liquid}$$

Subbarao and co-workers made seminal contributions to establishing the mechanism and martensitic nature of the monoclinic-tetragonal transformation by means of careful high temperature X-ray diffraction and thermal studies. The burst phenomena associated with this transformation has been clearly demonstrated through thermal analysis studies. Reliable lattice parameter changes from room temperature to 1400°C (i.e. in the monoclinic and tetragonal phases) have been reported. These studies have been extended to the phase relationships in the important binary system ZrO_2-Y_2O_3, which has gained prominence not only due to its ionic conductivity, but also due to transformation toughening caused by the volume change at the martensitic tetragonal-monoclinic transformation.

Mischmetal cobalt permanent magnets

The most significant discovery in the field of permanent magnets since the alnicos was that of RCO_5 where R = light rare earth, made by Strnat in the late 60's. Since India is one of the three major sources of rare earths in the world, Subbarao initiated a research programme on mischmetal-cobalt permanent magnets. Mischmetal is a mixture of rare earths occurring in their natural abundance and is much cheaper than purified individual rare earths. However, the magnetic properties of mischmetal based alloys will be poorer, since all the rare earth do not contribute to the magnetic behaviour as much as samarium. The mischmetal produced in India invariably contains some iron. Therefore mischmetal was considered to consist of a mixture of rare earths, treated as RE, and iron. Subbarao's group has carried out meticulous studies of phase relationships in the ternary system RE-Fe-Co and established the stability regions of important magnetic phases such as REM_5, RE_2M_{17}, etc., while discovering a number of new phases with useful magnetic properties. The phase relationship were elucidated not only by the conventional X-ray diffraction and metallographic techniques but also by thermo-magnetic measurements, since the ferromagnetic Curie temperature is sensitive to structure and composition.

Low thermal expansion ceramics

Subbarao and coworkers reported on the lattice parameter changes and bulk expansion of a number of oxide ceramics such as zircon, niobium pentoxide and sodium zirconium phosphate family. The influence of the crystal chemical parameters on the thermal expansion behaviour of the various members of the zircon family has been elucidated. The materials with anisotropic axial thermal expansion behaviour may exhibit low, even zero, overall bulk thermal expansion over selected temperature ranges,but suffer from micro-cracking on repeated heating and cooling cycles, as was first demonstrated in aluminium titanate by Buessem and coworkers. Subbarao and coworkers have shown the effect of grain size on such microcracking behaviour as also the conditions under which healing of microcracks originating from axial thermal expansion can take place. It has also been shown that microcracking does not occur in ceramics when the anisotropy in axial thermal expansion is minimised or eliminated through crystal chemical tuning, as in the system (Ca, Sr)$Zr_4P_6O_{24}$. The *a*-axis expands and *c*-axis contracts, on heating, in one of the end members, while reverse is true in the case of the other end member, so that an intermediate solid solution composition with near zero expansion in both *a* and *c* directions can be produced. While the two

end members exhibit micro-cracking on heating and cooling cycles, the intermediate composition does not.

Acoustic emission studies

Acoustic emissions are transient elastic waves caused by rapid release of energy within a material due to any microdeformation process such as microcracking, crystallographic phase transformation, twin formation, ferroelectric domain switching, etc. These can be detected by piezoelectric transducers, which convert the elastic waves into electrical pulses. Subbarao and coworkers exploited this technique to study microcracking due to anisotropic thermal expansion and its healing in (Ca, Sr) zirconium phosphates, niobia, etc., due to crystallographic phase transitions in ferroelectric lead titanate, superconducting $YBa_2Cu_3O_{7-x}$, zirconia ceramics, etc., due to domain switching during poling of piezoelectric lead zirconate titanate ceramics and due to electric fatigue in ferroelectric ceramics under cyclic electrical stress, as in memory devices. These studies have led to a deeper understanding of the underlying phenomena in each of these cases and, in some cases, to means of improving desired properties. The role of grain size, crystal chemistry, crystal structure, etc., has been elucidated. The acoustic emission technique can be used as a non-destructive, *in situ* tool to follow the progress of events in the use of materials.

Arising out of his commitment to teaching, Subbarao has authored or edited a number of books in various aspects of materials science.

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Chokkanathapuram Venkataraman Sundaram

Flowsheet development for the extraction and fabrication of rare metals and their alloys, and the development of special materials for specific functional applications, have been major components of the Metallurgy Programmes in the Department of Atomic Energy. Basic research in this field has involved the application of the principles of metallurgical thermochemistry to the extraction and purification of rare metal halides, metallothermic reduction of halides, carbothermic and aluminothermic reduction of oxides, pyro-vacuum metallurgy and studies on phase equilibria. Based on these extensive researches, pilot plants have been designed and operated successfully for the production of nuclear grade zirconium sponge (starting from India zircon), titanium sponge metal (starting from nubile) and beryllium metal and copper-beryllium alloy (starting from beryl). In all this work, special emphasis has been placed, simultaneously on the development of indigenous capability for fabricating sophisticated equipment and machinery.

Zirconium and hafnium

In water-cooled nuclear power reactors, an alloy of zirconium is extensively used as a cladding material for the uranium oxide ceramic fuel and also for the fabrication of structural components, such as pressure tubes and calandria tubes. The zirconium alloy offers advantages of low neutron absorption cross-section, good strength and ductility at the operating temperatures and excellent corrosion resistance in high temperature water.

The natural source material for zirconium is the mineral zircon which is a zirconium silicate invariably associated with a small percentage of hafnium. Zirconium and hafnium are extremely close in their chemical properties; on the other hand, hafnium is a strong neutron absorber and removal of hafnium is a very important step in the nuclear metallurgy of zirconium.

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In the first phase of the Department of Atomic Energy's research programme on zirconium (at the Indian Institute of Science, Bangalore), two entirely new processes were investigated: (i) selective vapour phase dechlorination of zirconium tetrachloride to form low-hafnium zirconium oxide, and (ii) selective reduction of zirconium tetrachloride with aluminium to form nonvolatile zirconium tri- and dichlorides. By adopting the second route, nuclear grade purity could be achieved in a two-step operation.

For the preparation of ductile nuclear grade zirconium sponge in kilogram quantities, starting from zircon, an integrated flowsheet was established involving (i) sintering of zircon with potassium silicofluoride to from potassium, zirconium and hafnium fluoride; (ii) fractional crystallization/purification of potassium zirconium fluoride; (iii) conversion of potassium zirconium fluoride to zirconium hydroxide and calcined zirconium oxide; (iv) chlorination of the oxide to zirconium tetrachloride; (v) magnesium reduction of zirconium tetrachloride in argon atmosphere to form zirconium sponge; (vi) pyro-vacuum treatment of zirconium sponge to remove magnesium and magnesium chloride; and (vii) crushing and grading of the sponge metal.

The above work provide the basis for the establishment of a full-scale production plant for zirconium sponge, of 80 tonnes per year capacity, which has been in operation at the Nuclear Fuel Complex, Hyderabad, since 1971, meeting the requirements of zirconium metal for the nuclear power programme. In the context of expansion of production capacity to meet the growing requirements, alternative flowsheets and equipment designs for larger batch reductions are under study.

Titanium

The extractive metallurgy of titanium bears close similarity to that of zirconium metal. There is a growing demand for titanium metal and its alloys in the country for applications in the aerospace industry and the chemical process industries.

After initial studies at the Bhabha Atomic Research Centre, Trombay, a pilot plant was established as part of the Nuclear Fuel Complex, Hyderabad, for the production of titanium sponge metal (in 755 kg batches). The flowsheet involved: (i) fluidized bed chlorination of rutile to produce crude titanium tetrachloride; (ii) purification of the chloride by H_2S treatment and fractional distillation; (iii) magnesium and sodium reduction of the purified chloride to produce titanium sponge/granules; and (iv) treatment of the sponge by pyrovacuum acid leach techniques, crushing and grading of the sponge. High

quality titanium sponge metal could be produced both by Mg reduction and sodium reduction.

Initial studies have also been carried out on the fused salt electrolysis of titanium tetrachloride, employing a special cathode.

The technology of titanium sponge metal production has now been transferred to the Defence Metallurgical Research Laboratory, Hyderabad, where the construction of a plant to produce the metal in 2 tonne batches has been completed.

Electro-refining of zirconium and titanium scrap

The conversion of zirconium and titanium metals to finished industrial components is associated with the generation of a considerable quantity of scrap, not all of which can be directly remelted for reuse. Electrorefining of the scrap metals using a fused salt bath offers an elegant route for reclamation. With special design cells, optimum parameters with respect to both composition, temperature and current density have been established to obtain the pure metal in kilogram quantities.

Niobium and tantalum

Niobium and tantalum co-occur in nature in the form of columbite and tantalite minerals. Noiobium finds important applications as an alloying addition to zirconium and also as a base for superconducting niobium-titanium alloys. Tantalum, by virtue of its high melting point, excellent corrosion resistance and special electronic properties, finds application in high temperature alloys, electrolytic capacitors and in the chemical process industries.

In the extractive metallurgy of both niobium and tantalum, high vacuum pyro-treatment and electron beam melting are important final refining steps, as the last traces of oxygen can be removed effectively in the form of volatile metal suboxides by such treatment.

Detailed thermodynamic analyses have been carried out on the reduction of the oxides of niobium, tantalum, zirconium and hafnium by carbon and aluminium. A new route has been established for the preparation of ziconium-niobium alloy and hafnium-tantalum alloy by carbide-oxide reactions.

Beryllium and copper-beryllium alloy

Beryllium metal finds extensive applications in aerospace and nuclear engineering by virtue of its unique physical and nuclear properties. There is also a

large demand for copper-beryllium alloy in the industry on account of its good fatigue strength and electrical conductivity.

The natural source material for beryllium is the mineral beryl, in which Indian resources are sufficiently abundant. Based on comprehensive laboratory studies, a flowsheet has been established for the preparation of vacuum hot pressed beryllium and copper-beryllium ingot starting from Indian beryl, and involving (i) sintering of beryl with sodium silicofluoride; (ii) extraction of sodium beryllium fluoride; (iii) preparation of beryllium hydroxide and pure crystals of ammonium beryllium fluoride; (iv) decomposition of ammonium beryllium fluoride to beryllium fluoride; (v) magnesium reduction of the fluoride to produce beryllium pebbles and copper beryllium master alloy; (vi) vacuum melting of beryllium, and (vii) lathe chipping, milling and vacuum pressing of beryllium powder to produce beryllium blocks.

A pilot plant is presently in operation for meeting the requirements of beryllium in atomic energy, space and electronics programmes.

Special materials development for fast breeder reactors

The development of fast breeder reactors forms the second phase in the Indian nuclear power programme. The fast breeder reactors will use plutonium in sintered ceramic form as the fuel, liquid sodium metal as the coolant and special stainless steels for many of the major reactor components. At the Indira Gandhi Centre for Atomic Research at Kalpakkam, basic and applied research programmes have been undertaken in the areas of materials science and materials development, chemistry, fuel reprocessing, reactor engineering and reactor safety. Structure-property correlation and performance evaluation of stainless steels at high temperature and in liquid sodium environment, simulation of radiation damage employing accelerators, chemistry of liquid sodium, physico-chemical measurements in plutonium-bearing fuels, equipment and process development for fast reactor fuel reprocessing, and development of liquid sodium technology are some of the major activities in the R&D programmes. The fast breeder test reactor (FBTR) that has now been commissioned uses a new fuel composed of 70% plutonium carbide, 30% uranium carbide, developed by the Radio-metallurgy Division at the Bhabha Atomic Research Centre, Trombay. The reactor will be a test bed for the testing of new fuel compositions and new structural materials in the reactor environment. These programmes will provide the experience and information base for the setting up of a commercial size Prototype Fast Breeder Reactor (PFBR) (500 MWe capacity).

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Mandayam Anandampillai Lakshmi Thathachar

Thathachar has contributed to several aspects of systems science such as learning systems, adaptive control and stability theory. Many of these are fundamental in nature and are characterized by ease of applicability and mathematical rigour.

Learning automata

There was a period in the evolution of the field of artificial intelligence when a majority of researchers were of the view that intelligent behaviour could be programmed into a computer. This view was particularly strong during the seventies and early eighties. This symbol-manipulation approach had its peak popularity at that time and the approach led to the development of a variety of expert systems. At the same time there was a relatively small band of researchers who were convinced that learning was an important component of artificial intelligence and were developing learning capability in man-made systems. Thathachar was among the few persons who foresaw the importance of studying learning systems. This view has been vindicated by the developments in the past decade. Thathachar's contributions have been particularly in the theory and applications of learning automata models.

Learning automata represent stochastic models of learning. They select an action at every instant based on the probability distribution defined over the set of actions, elicit a penalty or reward reaction from the environment and then update the probability of selecting the actions. The mechanism of learning is similar to that of a student learning with a probabilistic teacher and also to the multiarmed bandit problem familiar to statisticians[1].

Although algorithms with learning capabilities were prevalent in the earlier literature, they were developed on a heuristic basis. Thathachar provided a firm mathematical foundation for the design of learning algorithms by introducing the concept of absolute expediency and developing necessary and sufficient

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conditions for the property to hold[2]. He also proposed a new class of estimator algorithms[3], which are an order of magnitude faster than conventional algorithms and are hence attractive for applications.

In order to handle complex learning task, Thathachar has proposed hierarchical structures[4] and teams[5] of learning automata. In this context, he has worked out the information transfer needed between different levels of the hierarchy as well as the information exchange needed between numbers of a team, so that the entire system of automata converges to the global maximum of the objective function[6]. Using the concept to context vectors, networks of units each of which is composed of hierarchies and terms of learning automata have been developed. These form a novel type of stochastic neural networks. Convergence of such networks to the global solutions of complex learning problems have been shown with the use of specific types of algorithms[7].

Several aspects of multi-person decision making can be modeled by the theory of games. When the payoffs are stochastic and information is incomplete, identification of the right decision needs a learning approach. The role of learning automata in noncooperative games like the prisoner's dilemma and hierarchical decision making as in stackelberg games have been explored. The convergence theorems as well as simulation studies show that learning automata converge to Nash equilibria[8].

Learning automata are useful in routing messages in communications networks. It has been shown that they switch incoming calls among alternative routes, so that blocking probabilities are nearly equalized and close to the minimum[9]. Learning automata can optimize certain queueing systems. For tandem queues, a group of learning automata has been shown to converge to the optimal bang-bang solution with a probability arbitrarily close to unity. Furthermore teams and networks of learning automata have been applied to find optinal discriminant functions in pattern recognitions[6] and also to provide a convergent procedure for automatic labelling of objects in a picture, a significant problem in computer vision[10]. They can also be used for associative learning of Boolean functions[11].

Adaptive control

Control of a plant whose parameters are uncertain or unknown is a significant problem. The fundamental issue or adjusting gain parameters in an otherwise linear time-invariant system, so as to minimize an error index, has been studied by Thathachar. An elegant structural criterion which assures boundedness of the

signals in the system and convergence of the error to zero has been formulated[12]. The criterion only demands that a transfer function be positive real and this transfer function can easily be recognized on a block diagram of the system. The result provides a conceptual simplification in designing a variety of adaptive control, identification and observer schemes.

Stability theory

Stability of feedback systems with nonlinearities and time-varying elements is a challenging problem in control theory. Thathachar's contributions have been mainly in developing frequency-domain criteria for a variety of such feedback configurations. He has applied both Lyapunov theory[13] and functional analysis[14] to generate several classes of stability multipliers to suit different situations. The techniques have been extended to multiplicative feedback systems and systems with dynamical nonlinear subsystems. A major achievement in this area is a stability criterion for systems with power-law nonlinearities[15], which reduces to the well-known Nyquist criterion when the nonlinearity in the system is replaced by a linear gain.

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Handady Venkatakrishna Udupa

The main areas of research and development work of Udupa have been dye intermediates; textile technology; and electrochemical science and technology.

Dye intermediates

Udupa started research work as a research assistant in a CSIR scheme conducted by B B Dey at the Presidency College, Madras, on *Electrolytic reduction of nitro compounds leading to the manufacture of direct cotton colours*. As part of this programme, he did pilot plant scale work on the chlorination of benzene, phenol, chlorobenzene, nitrobenzene, toluene, nitrochlorobenzene, *p*-dichlorobenzene, etc. Kilogram quantities of these chemicals were made and the isomers separated by such unit operations as fractional distillation, steam distillation, fractional crystallization, etc.

For the conversion of nitrochloro compounds into nitroanisoles and nitrophenetoles, catalysts like manganese dioxide, lead dioxide and cuprous oxide were used[1-3]. Patents were taken on these novel aspects and several papers were published. Electrolytic reduction of nitro compounds in acid and alkaline media was studied and processes were developed for preparing compounds relating to *p*-aminophenol and benzidine series. Around 30-40 dye intermediates were thus made and processes standardized.

Research on co-deposition on tin and indium was carried out as part of a programme of work for Master of Arts degree in Industrial Chemistry at Columbia University in the City of New York. Later, at Ohio State University, a new technique involving the use of rotating cathode for the reduction of nitro-compounds to *p*-aminophenols[4,5] was developed, which formed the subject matter of the doctorate thesis. Use of rotating cathodes in the reduction of carbonyl compounds also formed a part of the programme of work for the doctorate degree.

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Textile technology

Udupa's two years' work at the Ahmedabad Textile Industry's Research Association included a comparative study of the bleaching of textile fabrics using calcium hypochlorite and sodium hypochlorite. It was found that cellulose degraded to greater extent with sodium hypochlorite than with calcium hypochlorite. The aim of another study was to ascertain the degree of fabric degradation by various physical and chemical processes followed in the textile industry. A process developed for giving semi-permanent finish to fabrics using a solution of hydrocellulose in sodium zincate solution was patented[6].

Electrochemical science and technology

Major part of the work of Udupa relating to electrochemical science and technology was carried out at the Central Electrochemical Research Institute, Karaikudi. This work covered fields like electroplating, metal powders, electro-inorganic chemicals, electro-organic chemicals, batteries, fuel cells, etc.[7]. New techniques were developed and novel approaches introduced in respect of known technologies.

Electro-inorganic chemicals[7]

A process for the production of cuprous oxide was developed incorporating a cell design for continuous operation[6]. A plant having 1000 A capacity cells was put up and operated.

As part of the programme of modernizing the technology for the production of electro-inorganic chemicals, research relating to the development of suitable insoluble anodes was taken up. This work resulted in the development of graphite substrate lead dioxide anodes for chlorate and perchlorate production.In this way, considerable reduction in graphite consumption in the chlorate industry became possible. For the perchlorate industry, the benefits were considerable saving in energy consumption and substitution of the costly platinum. Four plants of 1 tonne/day potassium chlorate production capacity were put up based on this technology. Two plants were put up for sodium perchlorate production and one for ammonium perchlorate production. During periods of conflict, potassium perchlorate was produced for meeting the defence requirements in 5000A capacity cells. Production of bromate, iodate and periodate using these anodes was also achieved.

Titanium substrate insoluble anodes (TSIA)[8,9] were developed for use in the chloralkali industry, resulting in 10-15% energy saving compared to the existing cells operating in the industry. This development is similar to the DSA developed

by De Nora's of Italy. The chloralkali industry has already largely replaced graphite anodes by these new metal anodes and more than 40% of the production today is with these anodes. Experimenting initially with 20 kA mercury cells, anodes were installed in 160 kA cells, operating at 8 kA/m^2 current density. These anodes have been successfully employed in 10 kA and 30 kA diaphragm cells also. The chloralkali industry has benefited immensely from the indigenous development of this technology.

TSIA have been employed successfully in the manufacture of sodium and potassium chlorate also, leading to considerable energy saving.

The development of a lead dioxide-lead bielectrode[10] as a substitute for platinum-lead bielectrode for impressed current cathodic protection is another example of platinum substitution research done for the industry.

Electro-organic chemistry[7]

(a) The rotating electrode technique[11] was successfully employed in the reduction of salicylic acid to salicylaldehyde, of nitro-benzene to *p*-aminophenol, and of nitro compounds to the corresponding hydrazo compounds in alkaline medium, and in the oxidation of glucose to calcium gluconate. Entrepreneurs were helped in setting up plants for the production of these chemicals. Improved mass transfer effects enabled the use of high current density in the production of these chemicals in cells of high capacity. Reduction of nitroguanidine, nitrosodimethyl amine and nitro urea was carried out at rotating cathode.

A high rate of reduction of nitro compounds suspended in acid electrolyte has been achieved using the rotating cathode for the preparation of a number of aromatic amines. Work was done on benzoic acid reduction to sorbitol and maleic acid and fumaric acid reduction to succinic acid. A 200 kg/day capacity plant for the production of succinic acid is being operated in Bombay.

(b) Indirect electrochemical syntheses using electrochemically generated reagents, such as chromic acid, titanous sulphate, bromine, periodate, and trivalent manganese ions have been developed. More than 15 aromatic amines have been made quantitatively from the respective nitro compounds using the titanous-titanic redox system. More than six plants have been put up for the production of calcium gluconate from glucose using the bromide-bromine redox system. Similarly,

aldehydes have been made from aromatic hydrocarbons using the manganic-manganous redox system. Dialdehyde starch was made using the periodate-iodate redox system. Saccharin was made using chromic acid.

(c) Reduction of nitriles to primary amines was carried out on carbon cathodes having black nickel, black iron and black cobalt deposits. A 500A cell was put up for this work. In work on the reduction of benzonitrile, benzyl cyanide, mandelonitrile, adiponitrile, dodecyl cyanide, cyanoacetic acid and 3-cyanopyridine, high yields of the respective primary amines were obtained at satisfactory current efficiencies.

(d) Oxidation of alcohols to aldehydes at electrodeposited oxide electrodes was investigated. Cathodes with deposits of silver oxide, ruthenium oxide, nickel oxide and cobalt oxide on different substrates were also tried.

(e) Use of the technique of interrupted dc electrolysis[12] with cathode rotation was found to give increased yields to the desired product, due to favourable conditions attained for the reaction of the intermediates formed. Substantial increases in the yields of *p*-aminophenol in the reduction of nitrobenzene and of pinacol in the reduction of acetone were achieved.

Recovery of secondary metals[11]

Two new techniques were developed for the recovery of secondary metals from non-ferrous metal sources. One of them relates to the recovery of zinc, copper, iron, lead, cadmium, etc. by direct reduction of oxides to give metal powders. Wastes from galvanizing industry, zinc oxide manufacture, hydrosulphite industry and copper utensils industry can be processed to give zinc and copper powders. A plant has been set up based on the technology developed for the production of iron powder from mill scale. Another technique developed involves suspension electrolysis to recover lead, zinc, etc. Plants have been put up for the recovery of zinc from galvanizing industry wastes.

Electrodeposition studies

Processes have been developed for the electroplating of zinc and lead from alkaline baths using a rotating cathode. Bright nickel plate was obtained from Watt's bath by cathode rotation. Variation in the composition of iron-zinc alloy under cathode rotation conditions was investigated. The influence of various

addition agents, such as CTAB, on deposit quality was investigated. Work was also done on brass-plating and cobalt-tungsten alloy plating.

Metal powder[14] deposition on substrates from which it would be easy to collect the powder has been investigated.

Batteries and fuel cells

Hollow carbon air-depolarized cathodes were developed and investigations carried out to develop secondary zinc-air batteries. Processes were developed for making Planté plates and high performance batteries for low temperature operation by incorporating carbon black in positive plates and organic addition agents in negative plates. Technology was developed for the manufacture of high energy density batteries for electric vehicles. Studies on constant current and constant potential charging of lead-acid batteries showed the latter procedure to be superior.

The possibility of using Indian manganese ore in dry cells was investigated. The technology for making dry cells on a small scale was developed and entrepreneurs were assisted in putting up plants for the same. High capacity sintered-plate nickel-cadmium battery technology was developed and the know-how released to industry. Sealed nickel-cadmium cells technology was developed and entrepreneurs were helped in putting up plants for the manufacture of these cells.

Considerable progress was made in the development of hydrogen-oxygen wet fuel cell and prototype batteries were tested for their life. Investigations were carried out to develop iron-titanium and other alloys for hydrogen storage; the stored hydrogen was used for running a two-stroke engine.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Harbans Lal Uppal

Physics of flow of water through pervious material and design of engineering works on sand foundation (1930-37)

A new method for determining the lines of flow through pervious material under works and uplift pressures on the floor was developed. Advantage was taken of the chemical reaction between potassium dichromate and silver nitrate and formation of black silver nitrate lines in the material–sand. Velocities of flow in strategic regions could also be determined.

The old theories of designs of works were exploded and new theories based on these studies were developed. Similarly, the determination of uplift pressures on the floor of the work helped to design economical, safe and sound hydraulic structures[1-8].

Energy dissipators below hydraulic structures and design of works (1935-39)

This is another important problem which faced the hydraulic engineers. Below the hydraulic structures on the rivers and the canals, deep and extensive scour holes occur which undermine the safety of the structure and necessitate large expenditures. After an indepth study extending over several years, effective and economical designs of energy dissipators were evolved. These comprised constructing staggered blocks at the toe of the glacy and at the end of the floor. The designs evolved form a part of the work for all structures not only in the country but even outside. The designs replaced the earlier devices, such as Rhebock cill and Inglice's baffle in use[9].

Anti-tank obstacles for amphibian tanks (on rivers and canals) (1938-41)

Anti-tank obstacles for amphibian tanks were evolved after research in the laboratories as well as in the field during the second world war. These proved highly efficacious and were adopted on rivers in the Kuram and Shinki valleys

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with great success. Earlier to this development, extensive long steel sheet pipes had to be installed on the river bed at a huge expenditure. The new devices, on the other hand, required only a shallow foundation. The assumptions made earlier anticipating deep scours were found to be incorrect. The new approach was based on siltation which occurs in the presence of tank obstacles; therefore, deep foundations were dispensed with.

Anti-tank obstacles on highways and roads (1946-50)

Anti-tank obstacles for roads and highways were developed. The method evolved consists in destabilizing the soil under the highway and roads and covering the surface with thick soil crust which while sustaining the load of light vehicles and jeep (3 tonnes) collapsed under the weight of the tanks. On the surface there was no visible sign of any destabilization underneath.

River training with the help of pitched surfaces (1942-45)

A new method evolved for training rivers and streams through central pitched islands is based on the principle of erosion close to the headworks at Sulemanki. It was also tried on actual works and on the prototype of the Satluj river, besides various models. This method aroused considerable interest in India and abroad and was hailed as a great advance on the existing methods for river training and control[11].

Design of surface profile of hydraulic structures with the help of models (1935-50)

Efficient and economic surface profile designs of various works, such as weirs, undersluices and regulator falls were developed based on intensive model studies. Besides designs for the reconditioning of the old structures, designs for the construction of the new ones undertaken in Punjab during 1934-47 were developed.

Research on water table behaviour, waterlogging, salinization of irrigated soils together with development of measures to ameliorate waterlogging and salinization (1952-85)

An area of 1.6-1.8 million hectares had got waterlogged in Punjab by 1955-62. The canal irrigation is not an unmixed blessing. Due to a variety of causes, water table in the irrigated tracts rises, ultimately causing waterlogging and salinity. This happened in the united Punjab as well as in the part of Punjab which remained in India after independence.

Considerable work was carried out in practically all the doabs of the Punjab. The causes of the twin malady of waterlogging and salinity and measures to ameliorate the condition were studied exhaustively over several decades.

Execution of extensive drainage system in the Punjab resulted in the construction of a network of drainage channels (several hundred in number) in half of the Punjab state. Some of the drainage channels were the largest ever constructed in any part of the world. Some of these channels carried a discharge of 340-400 cumecs and were 150-200 km long. These drainage channels made Punjab free from waterlogging.

Reclamation of saline and alkali land

Salination of soils generally takes place in the canal irrigated area in semi-arid tracts. In certain areas, high alkali soils also occurred. In the Indus plain, about 40,000 hectares are going out of cultivation every year on account of the formation of saline and alkali soils. Reclamation of such soils is very essential.

Work on reclamation of saline and alkali soils was taken up by Uppal after he joined the Punjab Agricultural University and economically and efficient reclamation methods were evolved. Reclamation of 30,000 hectares of saline and alkali soils per annum was done during 1954-65 with great success.

Building materials

Considerable work was carried out on building materials like soil, cement, concrete, kankar, surkhi, lime pozzolana and the effect of particles size of building material on strength. The aspects covered include design of mix for mortar for use in various structures, such as canal lining, concreting of weirs, barrages, dams; bond to steel strength of concrete as affected by the use of pozzolana and entrainment of concrete for different types of works. Special studies were carried out on pozzolana surkhi.

Water resources research

Besides considerable work on the water resources of India, a museum of water resources was developed at the Punjab Agricultural University campus, Ludhiana, where data on all the rivers of northern India, water and power potential, together with their utilization are depicted. Data on damage caused by floods and droughts are also presented for a number of years.

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Lakshminarayanapuram Ramier Vaidyanath

Vaidyanath has made very significant contributions in his chosen field of industrial metallurgy. His work has been mainly connected with fundamentals of fabrication and properties of materials. He has done extensive work on the autogenous bonding of metals with particular reference to the factors governing the autogenous bonding of mating surfaces. His subsequent work has been in the field of ferro alloys and currently he is working in the field of copper metal.

At the National Metallurgical Laboratory he worked on the frictional characteristics of metal and other surface related phenomenon of metal and materials which led to better understanding of the sliding and relative movement of mating surfaces. This was extended to a study in the field of tribology, mainly to study the micro-effects of rolling friction and effect of debris formed during the process of mating. Asperity deformation, welding of asperites, surface fatigue, depth of hardening and ensuing wear of particles in relation to the force required to move surfaces past each other were studied in detail. The work was related to a study of the problem of railways. All these studies led to the development of controlled friction material.

The study on friction material led to a better understanding of the inherent physical properties and surface characteristics of the materials used in various engineering applications. A deeper thought on this subject led to development of new processes for autogenous bonding of metals, which provided useful information for joining of metals without application of external heat, as for example, in the canning of fissile materials, where no external heat is applied for joining of cans. This work, which was of practical importance, led to a better understanding of the fabrication and joining technology and bonding of similar and dissimilar metals, where application of heat is not permitted for specific reasons.

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One of the concepts emanating from the study on friction has been applied to solid phase bonding. Solid phase bonding involves bringing surfaces to sufficiently close proximity for interatomic forces to provide the bonding force. After suitable preparation of surfaces it has been possible to autogenously roll bond two metals to create a strong joint. The potential metallic area available for bonding is equal to the extension that specimen has undergone, e.g. a 50% increase in length gives 50% of metallic area, etc. If these metallic region weld together, the strength of the junction is somewhat greater than to be expected from the simple viewpoint of joint strength anticipated. Taking account of this constraining factor of joining adjacent larger area of metal, a theoretical relationship has been derived, which relates joint strength to deformation. Experimental verification of this is available and a theory has been postulated. Details of the work have been published.

In another area related to the development work of ferro-alloys, Vaidyanath was responsible for instituting a study on the fluxless smelting in the production of an important ferro-alloy. The flux process is energy intensive and the fluxless process helped in energy saving which is an important consideration in the production process. Many advantages besides energy saving accrued through the adoption of the process, such as useful by-product and longer life of furnace lining and components. Clearly the energy intensive process was unsatisfactory in the long run and the adoption of the process led to considerable saving in the use of scarce raw material and in the overall cost of the process. In addition to the above, some work was taken up to employ usefully the by-product gas and its sensible heat.

For more than two decades Vaidyanath has been associated with the metal copper, a non-ferrous metal of great significance to industrial development in the country. Copper is a very important metal as it is used in all engineering applications, particularly in electrical and electronic applications, where several of its properties are considered very important factors. For a developing country like India, which to a large extent depends on import of this metal, it is important to see that this material is used judiciously. After an indepth study and analysis of the indigenous technology, Vaidyanath has helped the industries in solving many of the problems and helped in newer developments. Improvements in technology meant in-plant research and Vaidyanath's efforts in this direction have not only been for improvements in existing technologies but also providing help in adopting newer technologies to economies and extend the use of this metal. This resulted in the development of some of the electrical applications, drawing of

very thin gauge wires and developments of some of the sophisticated alloys such as beryllium-copper, etc., all of which were being imported.

In the area of indigenous production of copper Vaidyanath has helped the industry in overall recoveries of the metal and in by-product recoveries.

In adopting newer technologies and processes, many problems arose which needed considerable ingenuity to identify the problem areas of the industry. Some of the processes involved fundamental approaches such as processing wire from cast or rolled rods or improving the continuous casting and rolling process to produce thin gauge material, prevention of tarnishing during processing and storage or identifying a particular process route for producing material from initial to final stages more economically.

Apart from pilot plant studies, Vaidyanath has usefully employed the knowledge gained from his overseas visits and helped to translate some of the ideas through in-plant lecture courses, symposia, seminars and technical workshops which helped in the matter of adopting appropriate technologies and practices for process and product developments. It has thus been possible for Vaidyanath to help in production of some of the difficult alloys such as aluminium bronze, high conductivity coppers with alloying elements like chromium, cadmium, tellurium, etc.

Research projects were instituted on the use of copper in soil, plants and animal husbandry. The study has helped in identifying the effects of copper deficiency and the role of micronutrients.

In the field of standardisation, Vaidyanath has played a very significant role as the Chairman of the Standards Sub-Committee. He has helped in gradually developing standards of various groups of products, so that the products conform to end use applications. This was planned in a scientific manner. In this effort he has succeeded in considering the standards of various products imported from overseas countries, so that the indigenous manufacture not only conformed to overseas standards but also conformed to end use requirements, which is the ultimate objective. Development in this field needed improvement in practices right from raw material to finishing stage. This was successfully carried out by Vaidyanath with the help of his colleagues.

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Yedatore Venkatakrishnaiya Venkatesh

Arrival at the Indian Institute of Science

Venkatesh's arrival in 1963 at the Indian Institute of Science, Bangalore, after the formative period of veritable wilderness in Mysore, was a refreshing delight and an unalloyed joy to him. Research baptism was presided over by B L Deekshatulu, with whom he wrote up a few papers on the analysis of linear, finite dimensional dynamical systems with (i) a time delay, and (ii) time varying parameters.

As far as the first problem is concerned, the approximate results of Minorsky (in his classic book on Nonlinear Oscillations) and Bellman and Cooke's treatise (on Differential-Difference Equations) were the only accessible and intelligible material. The latter with its existence and uniqueness results terrified Venkatesh in the beginning. He developed a new, non-standard asymptotic expansion technique, for obtaining a solution to the linear differential-difference equation governing the system.

First phase of research

Venkatesh's attention turned to the stability analysis of linear and non-linear time-varying feedback systems, motivated by two factors : (a) the study of oscillations in time invariant nonlinear systems leads to a linear periodic differential equation, reminiscent of the classic Mathieu equation; and (b) there are physical systems (like the parametric amplifier) which are inherently time-varying.

A typical mathematical model used by control theorists is a feedback system with the linear time invariant dynamic part, G, in the forward block, and the linear or nonlinear, time-varying part, $\Phi(\bullet)\,k(t)$, as the feedback gain, where $\Phi(\bullet)$ is a memoryless non-linearity, and $k(t)$ is the time varying gain. The time interval under consideration is $[0, \infty)$. Of course, both the forward and the

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feedback parts are to obey some restrictions which are quite reasonable in practice. When the feedback part is merely a constant gain without the non-linearity, the frequency domain conditions which are necessary and sufficient for stability are attributed to Nyquist. It is well known that these conditions are equivalent to those that can be obtained from the classical Routh-Hurwitz results. One of the goals of researchers in this area is to derive such stability conditions that reduce to the Nyquist conditions when the feedback gain is constant.

Venkatesh's first major success in this direction related to the exponential stability of the linear time-varying feedback system. The stability conditions, which are sufficient, were obtained, in the Lyapunov framework, by a new class of time varying, quadratic Lyapunov functions and by solving a differential inequality (in the manner of C Cordunenau). These conditions seem to be the most general known to-date, and can be cast in the form of the Nyquist Criterion:

If the linear time invariant feedback system obeys the standard Nyquist criterion with a 'damping factor', β, and the integral average of the positive lobes of $\theta(t)$ (where $\theta(t) = \{(dk(t)/dt)/\ k(t)\}$) is bounded for all finite time, but its asymptotic limit (i.e., as the interval of integration tends to infinity) is bounded from above by 2β, then the linear time varying feedback system is exponentially stable.

This exponential stability condition for linear time varying feedback systems is distinct from the so-called circle criterion, whose special characteristic, one may recall, is that the rate of variation of the time-varying gain is unconstrained, but the frequency characteristic of the linear time-invariant part has to obey a rather severe inequality.

Similar results (including geometric interpretations) were obtained for nonlinear time-varying feedback systems with certain classes of nonlinearities, by adding an appropriate integral of the nonlinear part of the system in the quadratic form chosen as a Lyapunov function candidate in the linear case. These results constitute generalizations of the celebrated Popov theorem, which was meant for time invariant nonlinear feedback systems.

An interesting by-product of the new approach is that an alternative stability result can be derived involving a (negative) lower bound on the integral average of negative lobes of $\theta(t)$. In fact, one can think of a trade-off between a positive upper bound for the integral average of the positive lobes of $\theta(t)$, and a negative lower bound for the integral average of the negative lobes of $\theta(t)$. It is

interesting to note that the problem of how to arrive at such criteria in the Lyapunov framework is still unresolved.

Therefore, it came as a surprise to Venkatesh when he discovered that, by (i) analysing the input-output stability problem in L_2-space (as done by G Zames and others), rather than the state-stability problem which is the special feature of the Lyapunov framework; (ii) invoking the theory of positive operators in a Hilbert space; and (iii) solving differential inequalities (involving $\theta(t)$ obtained from considering some 'energy-line functions' containing monotonically decreasing and monotonically increasing functions of $k(t)$ in the integrand, it is possible to derive precisely such results for the L_2-stability of both linear and non-linear time-varying infinite-dimensional feedback systems. A special case of the general result so derived is a 'circle-type' of theorem, if $\Phi(\bullet)$ belongs to a certain class of non-linearities.

If the frequency function of the linear time-invariant part obeys some restrictions on its phase angle behaviour, then the nonlinear time-varying feedback system is L_2-stable, and no restrictions need be imposed on the time-varying gain.

One of the interesting by-products of these investigations was that Venkatesh could demonstrate that a certain result of R F Brockett (for a second order linear time varying system with a single time varying gain $k(t)$) on the maximal limits within which $k(t)$ could vary arbitrarily, without making the system unstable, was faulty. Brockett had attempted to use an important result of L S Pontryagin (known as the Maximum Principle) in optimal control to establish a result for the stability analysis of linear time varying systems. While the idea is an interesting one, however, the actual stability conditions on the time varying gain (which is faulty, as mentioned above) for the second order system were obtained by plotting the phase-plane trajectory.

The discussions Venkatesh has had with Mark Aizerman, in Moscow, in the context of a related result of one of his coworkers, while clearing up some mis-conceptions, point to the fact that the problem of combing the Maximum Principle with Stability (and Instability) Analysis is not yet satisfactorily settled.

When they realize that the stability conditions, obtained in the Lyapunov or positive operator framework, are only sufficient, they wonder whether they can at least establish to what extent these could be necessary as well. To this end, Venkatesh tried to derive instability conditions for linear and non-linear time varying feedback systems. As researchers in this field very well know, in almost

all the instability results of the literature, the method of contradiction is used in the attempt to prove instability, but the end results are mostly either trivial or somewhat faulty. In contrast with this, Venkatesh developed a constructive and direct way of establishing L_2-instability conditions, for linear and non-linear time-varying feedback systems, by using a not-so-well-known converse of the Cauchy-Schwarz inequality. In the course of deriving these instability conditions, it was shown that, in particular, two papers on instability, in leading journals, contained erroneous results.

The culmination of Venkatesh's efforts is the set of the most general input-output L_p-stability and instability conditions, where $2 \leq p \leq \infty$, for infinite dimensional time varying linear and non-linear feedback systems, obtained with the help of Riesz-Thorin interpolation theorem, the application of which requires, what one may call, a subterfuge technique. Moreover, deriving L_p-instability conditions requires the use of the converse Hölder inequality.

Venkatesh has derived, for discrete time systems, similar results which are significantly superior to the results of Ya Z Tsypkin (USSR) and others. Most of these things have been documented in his research monograph. The rest have appeared in the leading mathematical journals.

It is disconcerting to end this section with the candid statement that some of the basic problems in stability and instability, even as applied to linear, second order time varying dynamical systems, have not been resolved.

Second phase of research

The change of Venkatesh's research interests was also inaugurated by B L Deekshatulu. After his return from West Germany (where Venkatesh spent a stimulating time) Deekshatulu suggested that they should do something of practical relevance to the community, and 'not get lost in the wholly unreal world of symbols'. And they started basic work on remote sensing data acquisition and analysis—which, in the early stages amounted to the manual interpretation of colour infra-red images obtained locally by flying their own (i.e., the Institute's) Pushpak aircraft, mounted with Hasselblad cameras. They were, perhaps, the one of the very few pioneering groups in India working on this type of data processing for resources survey.

After B L Deekshatulu joined the National Remote Sensing Agency in 1976, Venkatesh was left alone to set up the Remote Sensing and Image Processing Laboratory. This aspect of his work was subsequently facilitated by a generous grant from the ISRO (in the form of a sponsored project). All the basic

software for image processing, and pattern recognition (for resources estimates) was developed (in the Department of Electrical Engineering, Indian Institute of Science) on a HP-1000 Computer interfaced with, among other things, a locally designed and developed colour image display facility, perhaps the first of its kind in the country at that time.

Any serious reseacher will find that most of the extensive literature in image processing contains purely *ad hoc* methods, and the claims made (for instance, in object recognition) by many authors are subjective, and cannot be confirmed even on images similar to those used by the respective authors. It was therefore only natural that his research interests zoomed, stage by stage, onto the finer, mathematically verifiable aspects of image analysis. This accounts for his current areas of work which, in brief, are: Mathematical modelling of the human vision system, and neural networks for object recognition.

Empirical findings in neuro-physiology and psycho-physics convince Venkatesh and coworkers that image processing in the (mammalian including human) visual cortex of the brain is not fundamentally in terms of the gray (or colour intensity) values, but in terms of specific features extracted from the retinal images. This extraction is achieved, so the neuro-physiologists have discovered, by the remarkable excitation-inhibition characteristics of the neural cells, which can be modelled by the so-called Laplacian-of-the-Gaussian filter (also known as the Mexican Hat) functions. It is found that this filter, in combination with a detection mechanism for locating the change from positive to negative values of the signal, extracts, in essence, the boundaries (or outlines) of objects in an image. These outlines, which are, in fact, called the zero-crossing contours of the image, are known to contain a considerable amount of information.

It has been conjectured that the human brain also represents the physical world in terms of some such contours. A natural question is whether one can mathematically reconstruct the image of the physical world using only these contours.

In an attempt to solve this problem, Venkatesh has developed a new framework using generalized Hermite polynomials, and dispensed with the standard but unrealistic assumption of bandlimitedness of signals. As D Slepian has explained in one of his interesting papers, physical signals are neither bandlimited nor space-time-limited. What matters is the effective bandwidth (and, correspondingly, effective spatial/time spread) of the signal, whether it is one-dimensional (like speech) or two-dimensional (like image).

By exploiting the special properties of the Hermite polynomials, Venkatesh has shown that a unique reconstruction is possible from the (partial) information of zero-crossings of the signal, if they are given the space-bandwidth product or the space-bandwidth ratio. The same framework can be used for reconstruction of signals from partial information of the type: (1) Fourier phase only; or (2) Fourier magnitude only.

Another interesting result using the Hermite polynomial framework is the possibility for creating wavelet-like arrays for multi-scale decomposition of signals.

Other contributions, which could be treated as by-products of Venkatesh's work on image processing, are in the areas of: (a) quadtree data structure for binary image representation; (b) stereo-pair image analysis; and (c) pattern recognition using neural network.

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SECTIONAL COMMITTEE — V

Earth Sciences

Atmospheric Sciences, Geography, Geo-Sciences and Oceanography

Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Fakhruddin Ahmad

Ahmad got deeply involved in research, at first basically in Gondwana geology. However, at that time one could hardly work on Gondwana geology, without getting involved in continental drift and palaeogeography, and these absorbed Ahmad's entire energy.

Ahmad's major work on the subject that came out as a volume (Memoir Geological Survey of India, Vol 90) in 1961 was titled as *Palaeogeography of the Gondwana period in Gondwanaland, with special reference to India and Australia, and its bearing on the theory of continental drift.* It was a comprehensive study on the subject.

Earlier Ahmad had published another interesting paper on *Glaciation and Gondwanaland* (*Rec Geol Surv India,* vol 86, pt 4) pointing out that the south polar ice cap had been migrating from north-west Africa in the Ordovician to Australia and India in the Permian. The southern continents were then together and palaeomagnetic evidence on polar migration was then not available, Ahmad's interpretation was that it was a consequence of continental drift. Later it transpired that it was the consequence of actual polar migration. The North Pole, too, must have been migrating, but field evidence for this pole was not available. Indeed, it is still not available, perhaps because this pole must have been to the north of Canada, and the area continues to be *terra incognita.*

An interesting study that came out of Ahmad's pen deals with contemporary epeirogeny in the Indo-Gangetic basin. Evidence on contemporary epeirogeny is hard to come by, but Ahmad has provided a lot of it and most of it is interesting.

Orogeny, geosyncline and continental drift is a hallmark paper and deals with the extremely interesting aspect of orogeny, based on geosynclines and its

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bearing on continental drift. On the other hand *Flood traps through space and time* is a comprehensive review of flood traps from all over the world and their bearing on geotectonics and continental drift.

The future of the World mineral resources and the Middle East (in French) is an exhaustive study of the known mineral deposits (except oil) in the Arab countries in particular, and Muslim countries in general, presented at the World Muslim Solidary Conference in Saudi Arabia in 1976.

The Gondwanaland concept was strongly supported by palaeontological evidence, presuming that many of the forms were entirely endemic—this applied to plants, invertebrates as also to vertebrates and even to insects—for Gondwanaland was supposed to have been an entirely independent continent, separated by a deep ocean from the northern continents and no lifeform could migrate from or to Gondwanaland. Ahmad, however, demonstrated that never in the entire geological history was there any such restriction and the forms migrated freely from Laurasia to Gondwanaland or in the opposite direction. Being perhaps the earliest study on the subject, the paper changed the entire thinking. It may be noted that Wagener was not a supporter of the two-continent concept, and it was Du Toit who introduced it. Obviously he was wrong, and today, plate tectonics as well as expanding Earth concepts support the view that Pangaea started breaking in the Triassic.

Earlier, Ahmad contented that convection current inside the Earth is just not possible. He has produced convincing evidence that the Tethys, as many believe somehow, did not separate Laurasia and Gondwanaland, nor was it a large triangular ocean extending from the Pacific coast of China and ending in a point in Spain. The fact is that it was an epicontinental sea that extended from the Himalayan region in the south to the southern part of Siberia, and continued over large parts of Europe and extensively over North America. Thus it extended from the western Pacific to eastern Pacific, without a serious break. And naturally there were wide gulfs emanating from it, one extending from Punjab to north eastern Africa, and another to cover Arabia.

Ahmad's study of the origin of the Rajasthan desert is unusually interesting, drawing a lot of data from history and Hindu mythology. He places the beginning of the desert conditions around 1500 BC when the Saraswati river, flowing into the Gulf of Cutch suddenly disappeared, because its major tributaries—Sutlej and Beas on the west changed their courses and Drishadwati on the east dried up having been captured by the Yamuna. A mass movement of Aryans, who inhabited the eastern bank of the Saraswati, took place and they had no alternative

but to cross the Ganges and enter U P. The Dravidians resisted this and there was a major battle at Kurukshetra. The Aryans were victorious and the Dravidians suffered for hundreds of years as a consequence. Written in about 400 AD and carried by word of mouth for around 1800 years the mythological tale that it was fought between two brothers has no basis in history.

Of late Ahmad has been keenly interested in the Tsangpo Suture, that has a very powerful support from the plate tectonicists, who happen to be in a commanding majority amongst the geologists. Yet, Ahmad does not agree with this majority for the evidence against it is irrefutable. The existence of Gondwana glaciation north of the feature, when India was supposed to have been in the southern hemisphere is accepted by all. The ice moved from the south (? India) and carried Gondwana fauna and flora. The area from the Himalayan region northward was under the Tethyan sea and no satisfactory explanation has been offered for the phenomenon so far. Also of significance is the fact that the collision is supposed to have taken place in the Miocene-Pliocene but the ophiolites are of Carboniferous age, and hence around 100 my older than the collision and obduction. Important also is the fact that contact metamorphism is present on both the flanks, and unless the Indian plate was in its place when these Carboniferous ophiolite intruded, the metamorphism of the Indian plate was just not possible. The lavas have extensive crystal settling and carry crystals of diamond, poissanite and other minerals, indicating that the origin of the lava must have been at a temperature of 1105-1240°C, a pressure of 27-46 kb and therefore it must have originated at a depth of 80-140 km. These lines of evidence have been discussed by the French and other teams as also by the Chinese geologists independently. However, an exceedingly interesting line of evidence that has emerged from Ahmad's work is that once the ophiolites had appeared in the so-called Tsangpo Suture, a wall of hard basic rock, 8-20 km thick stood in the area. Whether it originated from the ocean bottom, as the plate tectonicists believe, or from deep down in the mantle is immaterial. Once the wall was in place, it was impossible for the Indian plate to cut through it in the process of the supposed underthrusting. Yet palaeomangnetists insist that it is moving even to this day, millions of years after the event, at the rate of 1-5 cm/year!! Of similar significance is the fact that there is no feature north of Assam, the Tsangpo feature coming to an end at Rinbum, south-west of Lhasa, in which the Indian plate in front of Assam could have subducted. Then where is it gone? No explanation has over been offered. These lines of evidence do not support the view that the ophiolites are obducted ocean bottom, yet the plate tectonicists keep

on ignoring these, just do not mention them and yet they go on insisting that collision has taken place.

Ahmad, on the contrary, is a staunch supporter of the expanding Earth concept and has been writing on the subject for quite a few years. A very original study that came out of his pen deals with the palaeodiameter of the Earth. The position of the pole can be determined by (a) palaeomagnetism and (b) palaeoclimate and the existence of the icecap of the time. When these two lines of evidence agree with each other, one can be certain of the then position of the pole. Based on these Ahmad has pointed out that the Cambrian South Pole was in the north-west of Africa and the North Pole in the present day Indian Ocean area, where then stood the Tasmanian island. The icecap was in the north-western part of Tasmania. This yielded a diameter of 50% of existing diameter. On the other hand, the Permian South Pole was south-east of South Africa and the North Pole was near Verkhoyansk in Siberia, suggesting a diameter about 55% of the present diameter. This does demonstrate that: (a) the Earth was considerably smaller in diameter in the past, (b) that it increased but slowly from the Cambrian to the Permian, (c) however it seems to have increased considerably rapidly in diameter since the Permian, i.e. the rate of increase is apparently becoming progressively faster. Where the future lies is not known to science.

The above brief review of Ahmad reveals that he has not been confined to a single line of research and has contributed to a variety of subjects. Thus, he has covered subjects like glaciation, contemporary epeirogeny, diameter of the Earth, geosynclines, palaeontology, traps, faults and tectonics, origin of a desert and so on. Of late he has, however, been concentrating on the geology of Tibet, with special reference to plate tectonics and expanding Earth concepts, strongly supporting the latter. It seems that at least in the case of the Indus-Tsanpo Suture the plate tectonicists have been deliberately ignoring evidence that does not fit in with their concept and this, to say the least is hardly science. It is not that it would last, for sooner or later scientists would realize the truth, and condemn the untruth, howsoever powerful the lobby may be.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Ramakrishna Iyer Ananthakrishnan

Ananthakrishnan's research contributions relate to Rayleigh scattering and Raman effect, some aspects of Solar physics and meteor astronomy and studies in meteorology/atmospheric physics.

Rayleigh scattering and Raman effect : The early research work of Ananthakrishnan at the Indian Institute of Science, Bangalore (1933-37) relates to studies in Rayleigh scattering by liquids and gases and Raman effect in liquids and crystal powders. He was among the first few workers to study the Raman spectrum of heavy water (a rare substance in those days) and compare it with the Raman spectrum of ordinary water. He also investigated the Raman spectra of several organic liquids and detailed their spectral characteristics. He devised a new experimental technique using complementary filters to study the Raman spectra of crystal powders, which he successfully employed to investigate the spectra of several organic and inorganic substances in the crystalline powder form. One of the findings of this study was the determination of the structure of the molecule of phosphorous acid (H_3PO_3) which was rather controversial in the chemical literature. The presence of frequencies corresponding to the P-H bond vibration in the Raman spectrum showed that the constitution of the molecule is $O = P\begin{smallmatrix} -H \\ -OH \\ -OH \end{smallmatrix}$. This conclusion was confirmed by the Raman spectrum of sodium phosphite (Na_2 HPO), which also showed frequencies corresponding to the P-H bond vibration. The Raman spectra of water of crystallisation in several substances were also successfully studied by the new technique.

Solar physics : Ananthakrishnan's research in solar physics relates to the period that he worked at the Solar Physics Observatory, Kodaikanal (1946-54), which was then part of the India Meteorological Department. He carried out spectrophotometric and some other studies relating to sunspots. He also made a comprehensive investigation of solar prominences in H-alpha, utilising the data of spectroheliograms of the Kodaikanal observatory for the period 1905-1952,

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covering four solar cycles. An interesting finding of this study was the remarkable progression of prominence activity from the equatorial to the polar latitudes of the sun, from the maximum to the minimum of the sunspot cycle.

Meteor astronomy : During a period of about six months that he spent at the Dominion Astrophysical Observatory at Ottawa (Canada) in 1960, Ananthakrishnan carried out some studies on the light curves of meteors using photographic records of meteor trails obtained with super-Schmidt cameras at two stations in north Canada.

Meteorology/atmospheric physics : The scientific studies of Ananthakrishnan in meteorology/atmospheric physics belong to the period of his association with the India Meteorological Department (IMD) and later with the Indian Institute of Tropical Meteorology (IITM), starting from 1937. Many of these studies were carried out in collaboration with colleagues in these institutions.

Thermodynamic diagrams are used in meteorology for depicting the data of aerological soundings. One of Ananthakrishnan's early contributions was preparation of such a diagram (tephigram) suitable for the Indian area. This diagram prepared around the 1940's has been in regular use in the IMD for several decades.

The aerological data of Indian stations have been utilised for a number of studies. These include changes in the thermal structure of the atmosphere associated with the passage of western disturbances in winter, changes leading to the onset of the summer monsoon, occurrence of inversions and stable layers in the atmosphere, monthly variations in the precipitable water vapour, and changes associated with contrasting rainfall situations during the southwest monsoon season. The meridional reversal of temperature and pressure gradients across the country and the associated changes in the wind circulation leading to the onset of the southwest monsoon show a progression from the surface upwards and from the tropopause level downwards towards the mid-troposphere in the course of about 2 months beginning from the middle of March, when pressure gradient across the country reverses at the surface.

The upper wind data from Indian stations have been utilised for several studies. Changes in the zonal and meridional circulation accompanying the onset and withdrawal of the southwest monsoon, vertical structure of high level easterlies during the monsoon months, interrelation between fluctuations in the low level westerly and high level easterly flows, comparison of actual and

geostrophic winds, biennial oscillations and diurnal variation of zonal and meridional winds are some of these studies.

Daily rainfall data of coastal and island stations in the southwest were examined for May-June to arrive at criteria for fixing the data of onset of the monsoon over Kerala. This study has been refined by utilising the daily area averaged rainfall from a dense network of stations over Kerala. Diurnal variation of rainfall has been studied utilising the data of stations with self-recording raingauges. This study showed that the total southwest monsoon rainfall is received at individual stations in a duration of about 200 hours or less; half the total rainfall associated with heavy rain is received in about 10% of the total duration. The statistical behaviour of long period daily rainfall at several stations was studied leading to some new findings about the rainfall distribution. The rainfall patterns at several stations were studied utilising long-period average rainfall for 5-day intervals (pentad rainfall). Several stations show a rainfall minimum around the middle of August. This appears to be a climatological singularity in the southwest monsoon rainfall arising from the north-south migration of the ITCZ across the country.

It has been known for a long time that the 24-hourly pressure tendency at tropical station show an oscillating behaviour with a quasi-periodicity of 4 to 5 days. Long period data of several stations were analysed to study the statistical features of this oscillation and its spatial progression.

The hourly pressure data from a network of 62 stations equipped with microbarographs were utilised to study atmospheric tidal pressure oscillation over India. The mean hourly pressure values for the individual months were harmonically analysed for all the stations to study the seasonal variations in the amplitudes and phases of the first four harmonic components. The diurnal wave $S_1(p)$ and the semi-diurnal wave $S_2(p)$ together account for almost the entire variance at all the stations with large seasonal variations. $S_1(p)$ attains maximum amplitude in the hot weather months March-May and minimum amplitude in the southwest monsoon and winter months. $S_2(p)$ shows more organised behaviour compared with $S_1(p)$ at all the stations. It attains largest amplitude in the months January-April and minimum amplitude in June-July. The percentage variance accounted for $S_2(p)$ has seasonal variations opposite to that of $S_1(p)$. The phase of $S_2(p)$ is found to be latest in July and earliest in November, the mean times of first maximum being 10.43 hr and 9.78 hr local time, respectively. At several north Indian stations the amplitude of $S_1(p)$ exceeds that of $S_2(p)$ in the hot weather months.

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Uppugunduri Aswathanarayana

Any fundamental study of the earth as a physicochemical system has to reckon with the formidable problems arising from not only the enormous size of the system, and the numerous and complex variables involved, but also with the vast stretches of time (running into billions of years) during which the earth processes took place. This daunting task was sought to be accomplished by the earth scientists by applying physical, chemical and mathematical tools to unravel the nature and magnitude of the earth processes and the modes of their interaction during the geological time. Radioactivity has proved to be a powerful tool in this regard, and Aswathanarayana has been a pioneer in radioactivity studies in India. Most of the work done by him and his associates has been reviewed in his recent publication.

Radiometric dating and geochronology of India

Aswathanarayana initially started dating the radioactive minerals by U-Th-Pb chemical method, as he did not then have access to a mass-spectrometer. All the lead present in the mineral was deemed to be radiogenic, and as it is usually so in old U-Th minerals, the errors arising from this assumption are not serious. This study resulted in the delineation of the broad framework of the Archaean orogenic cycles of India. Later, isotopic methods involving the Rb-Sr and K-Ar methods of dating whole rocks and mineral separates and lead methods of dating of radioactive minerals and galenas were employed to delineate the metamorphic chronology of the Precambrian belts of India. His notable contributions are to show that (i) the sedimentation in the Cuddapah Basin started around 1500 Ma ago, subsequent to the Eastern Ghats orogeny, about 1600 Ma ago, (ii) there had been more than one episode of charnockitization in the Precambrian terrains of South India, and (iii) the Eastern Ghats rocks were subjected to a profound and widespread metamorphic impulse around 450-500 Ma ago (Indian Ocean Cycle).

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A comprehensive synthesis of the geochronological history of India from the Archaean (ca 3800 Ma-tonalites of Bihar) to the Middle Miocene (16 Ma) Himalayan orogeny, has been attempted recently by Aswathanarayana.

Temporal, spatial and geochemical evolution of Deccan Traps

The origin, geochemical hetérogeneity and possible nature of the upper mantle source of the Deccan Traps have been investigated using major element, trace element and Sr isotope data, in conjunction with geologic setting and structure. A number of critical trace elements (K, Rb, Sr, Cs, Ba, U, Th, Ta, etc., determined mostly by neutron activation analysis) and Sr isotopes have been used to develop petrogenetic models in respect of the Mount Girnar Complex, western India. There is evidence for the "continentalization" of the oceanic-type, low-K tholeiites. The abundance of tantalum has been used to discriminate between *ortho*- and *para*-syenites. A new type of tantalum resource (in the form of easily separable pyrochlore in microsyenite) has been identified.

K-Ar age dating and Sr isotopes have been made use of to study the temporal evolution (50-42 Ma) and magma genesis (lava flows which have undergone crustal contamination, and "pristine" lavas) of the lava sequence of the northeastern part of the Deccan Traps around Sagar, MP, India. The history of effusion of the Deccan Traps was sought to be reconstructed, ranging from the earliest about 100 Ma Lower Cretaceous flows in the Dhanduka sequence, Saurashtra, Gujarat, to the waning phase of the Deccan Traps (42-31 Ma, Eocene-Oligocene) of upper flows of Koyna, Dohad, etc., with 65-60 Ma Palaeocene peak which is most widespread, particularly in western India.

Stable isotopes and chemical indicators of palaeo-environments

Chemical characteristics (major elements, trace elements and radioactive elements, and particularly Co/Ni, V/Cr, Th/U ratios) and stable isotopic abundances ($\delta^{13}C$ and $\delta^{18}O$) have been used in conjunction with geologic setting, sediment characteristics, sediment structures, etc., to delineate the palaeo-environments of the Late Proterozoic Chhattisgarh Basin, India. It has been shown that the Charmuria limestone formation (490 m thick) was formed in a subtidal environment, with a turbidity level high enough to prevent the development of stromatolites. The younger Chandi limestone formation (670 m thick) was formed in an open, intertidal environment, marked by the abundant development of SH-V stromatolites.

Geochemical and stable isotope study of the abnormal fluoride waters of northern Tanzania

The endemicity of skeletal fluorosis in parts of northern Tanzania is attributed to the ingestion of more than 20 mg/day of fluoride, largely through the drinking of highly fluorous waters (with about 10 mg/litre of F^-) and partly through eating "magadi" (highly fluoridic, sodium bicarbonate encrustations used as salt) and food. Geochemical and stable isotope (δD and $\delta^{18}O$) techniques have been employed to trace the source of high fluoride concentrations (principally alkali basalts, nephelinites, carbonatites, with F sometimes being present in the ashfalls in the form of highly soluble villiaumite) and the pathways of movement of fluoride through soils, waters (surface, ground, spring, pond, etc.) vegetation and food, to man.

Geochemical dispersion patterns of radioactive elements and base metals

A large number and variety of terrestrial materials (rocks, soils, water, plants, sea-floor sediments, etc.) have been examined for their radioactivity, and, in conjunction with relevant geochemical data, have been related to the mode and environment of formation of the material concerned.

On the basis of Th/U, U/K, K/Rb, $Fe_2O_3/FeO+Fe_2O_3$, Sr-86/Sr-87, a petrogenetic model was developed for the Closepet Granite of Karnataka state. It involved a two-stage history: (i) palingenesis, starting from the 2600 Ma Peninsular Gneiss, and (ii) metasomatism involving enrichment in K, Pb, Rb, Th, and depletion of Sr, Cs, etc. It has been shown that Th/U and U/K ratios are capable of being used as aids in prospecting for uranium and thorium deposits in peninsular India. On the basis of contents of U, Th, K, etc. (determined by neutron activation analysis) of several mantle-derived rocks, models have been developed for the mineralogical, chemical and isotopic composition of the model upper mantle. The primary and secondary dispersion patterns of base metals in the Mamandur prospect, Tamil Nadu, have been delineated and a possible base metal indicator plant (*Waltheria indica*, Sterculiaceae) has been identified.

Aswathanarayana developed a comprehensive model to account for the pattern of distribution of the monazite-bearing heavy mineral sands along the west and east coasts of India. The pattern is a consequence of the operation of the following factors cumulatively: lithology, structure, weathering and erosion of the geological formations constituting the primary provenance, the geomorphic history and physiography, the gradient of rivers and the quantum of river discharge, the nature of the alongshore currents, events leading to the emergence of land and flooding of river valleys, etc.

Environment and health in eastern and southern Africa

The radiation exposure arising from the mining, milling, concentration, storage and application of the radioactive phosphorite of Minjingu, Tanzania, has been found to be generally below the permissible levels of exposure. The endemicity of fluorosis (dental mottling and *genu valgum*) in northern Tanzania arises out of drinking highly flourous waters (with more than 8 mg/l of fluoride) and consuming "magadi" (sodium bicarbonate encrustations with very high fluoride content of more than 1000 ppm) as salt. Improper agricultural practices, deforestation and overgrazing have led to disastrous soil erosion in Sub-Saharan Africa. Food crops and vegetables grown in such soils are deficient in nutrient elements. Deficient intake of iodine (about 25 μg/d, as against the recommended intake of 150 μg/d per capita) has led to severe iodine deficiency disorders (IDD). Goiter of over 60% and cretinism (physical and mental retardation) of 1-10% are endemic in part of Tanzania and Kenya. Models have been developed for the management of the natural resources of the countries of the eastern and southern Africa in ecologically-sustainable and economically-viable ways.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Pronab Kumar Banerjee

Banerjee has made contributions in different branches of Indian geology, covering Precambrian stratigraphy, exploration geochemistry, ore deposits associated with mafic and ultramafic rocks of Eastern Indian Shield, patterns of Precambrian metallogeny, laterites and bauxite deposits of India and Quaternary sediments on the continental shelf of India.

Precambrian stratigraphy : By systematic geological mapping on scale 1:63,360 covering more than 1300 sq. km in Sundergarh district, Orissa, Banerjee unravelled for the first time the superposed antiformal structure on an inverted stratigraphy of the Gangpur Group. Imprints of a late thermal metamorphism associated with emplacement of granite plutons on the moderately metamorphosed and easterly plunging refolded antiform were identified by him. Complex culminations and depressions on the regional plunge to the east were also identified in sector-wise architectural analysis.

Farther north in West Singhbhum in the area south and southwest of the Ongarbira Hill, Banerjee defined a new, lowly metamorphosed, shelf sediment assemblage older than the Kolhans but younger than the "Chaibasa Stage" rocks of Dunn. He named this formation as "Sahedba sedimentaries".

Using greenschist facies, chromiferous ultramafic rocks as a geochronological index in the area north of the Brahmani river in Sukinda tahsil, Cuttack district, Orissa, Banerjee established that the Khondalites and charnockites of the Mahanadi valley, which are intruded by these ultramafic rocks must be older than the Mahagiri quartzite and associated sequences, which are either co-folded with these ultramafic rocks or are younger, as indicated by the presence of cross-laminated chromite quartzite, as a constituent facies, in some of these assemblages.

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Farther northwest in Sambalpur district, the Deogarh quartzites underlying the Bonai volcanics are associated with conglomerates containing clasts of pink K-feldspar, which occur as an integral part of a K-granite along the tectonised border between the Raimal granulites and the Bonai granite to its north. Banerjee argued on such geological evidences that the Mahanadi valley granulites are possibly older than the Bonai greenstone sequence to its north; and envisioned a process of Precambrian continental accretion, the roots of the oldest continental lithosphere being presently exposed as the Khondalites and charnockites of the Mahanadi valley. Strong mafic magmatism during Proterozoic I and a comparatively stable lithospheric growth during Proterozoic II are recorded in the Gorumahisani and Bonai Iron Formations followed by the Darjin and Gangpur fold belts, according to him.

Precambrian metallogeny : In the early sixties, Banerjee discovered the first nickel laterite deposits of India in the Sukinda ultramafic field, besides delineating large resources of high grade chromite here on the basis of structural and geochemical investigations. Later in the late seventies and early eighties, the discovery of a basemetal sulphide deposit below thick overburden of partly exhumed laterite saprolite at Adas, Sambalpur district, owed much to his extensive knowledge of laterites, although at Malappuram, Kerala, the strong basemetals anomaly in a sand bar eluded his follow up, in the late eighties, to the source deposit.

According to Banerjee, a majority of the endogenic mineral deposits in East and South Indian Shield occupy linear tracts of ancient rifting, sea floor spreading and collision between Archaean continental nucleii. He demonstrated this frame of plate tectonics controlling Precambrian endogenic metallogeny in a series of publications.

Precambrian mafic volcanism : Banerjee's study of Precambrian mafic volcanics in parts of Bihar and Orissa depicted not only a broad similarity between ancient and modern mafic magnetic eruptive environments, but also the operation of similar tectonic processes in the shaping of the continental margins. While the Gorumahisani greenstones were found to be analogous to Red-Sea-type sea floor spreading zones, to the Bonai volcanics occurring between two granitic cratons were diagnosed to have affinity with continental to island arc volcanism. The best illustration of Precambrian island arc volcanism was found in the linear stretch of Dalma volcanics, a large part of which appears to have erupted explosively under submarine conditions. On the basis of strong structural disharmony between the rock sequences lying to the north and south of this

volcanic chain, Banerjee concluded that these basalts possibly define a zone of collision between two Precambrian field belts, akin to a back arc magmatic chain, caught between two colliding continental blocks. According to Banerjee, the Dalma volcanics outcrop in the form of a stack of faulted blocks, piled one upon another, in the nature of steep dipping imbricate thrusts.

On the basis of field relations and available isotope geochronological dates, Banerjee argued that the Dangoaposi, Ongarbira and Simlipal basalts were erupted possibly close together in time and overlapping the emplacement of the Newer Dolerite dyke swarm across the Singhbhum granite. He envisioned that a shallow plume had bubbled up below the Singhbhum lithosphere near the end of Proterozoic I, when globally the continental crusts were settling down to a phase of comparatively stable evolution. Validation of this concept will depend upon a large volume of high quality isotope dates on adequately constrained samples; and might provide some ingredients for a paradigm shift involving the duality of energy transfer from the core to the crust of the Earth, by plate and plume tectonics, across variable combinations of oceanic and continental lithospheres during the last three billion years.

Laterite and bauxite : As the global co-ordinator of UNESCO-IGGP Project 129 (lateritisation processes),. which continued from 1975 to 1983, Banerjee played an active role in interdisciplinary studies on laterites, and helped in establishing linkages among pedologists, microbiologists, geochemists, economic geologists and engineering geologists in a comprehensive study of this humid, tropical weathering product. He developed a comprehensive framework of morphologic and genetic models for the laterites of Orissa. Later, his researches on the coastal laterites of Kerala and Karnataka revealed that some of these profiles carry records of past climatic reversals, while the ironstones, extending along the East Coast intermittently from the Medinipur district (West Bengal) to Cuddalore (Tamilnadu) were found to have developed during the arid cycles of the Pleistocene, when sea level had fallen substantially.

Quaternary marine sediments : Banerjee developed a three-stage model for the genesis of low grade multimineral placer deposits on the inner continental shelf of East and South India, as a part of a generalised sea level curve for the East Coast of India covering the last 20 kyr. The central importance of this curve is the conclusion that sea level fell in a number of stages and again rose in stagess, sometimes fast; the highest stand is a few thousand years old, long before anthropogenic interventions came into play, and the latest sea level fluctuation corresponded to the Little Ice Age (1400-1850 AD).

As the leader of some scientific cruises, prospecting for sulphide deposits in the Andaman Sea (a back arc), Banerjee recovered and analysed the significance of some feeble base metals anomalies in the seabed sediments of the volcanic island of Narcondam.

In summary, Banerjee's contributions illustrate a mix of orthodox geological field and laboratory studies with model driven approach for broad understanding of earth processes.

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Shashi Bhushan Bhatia

Bhatia has made significant contributions to varying aspects of palaeontology, biostratigraphy, palaeozoogeography and palaeoclimatology. His pioneering works on fossil and recent foraminifera, ostracoda and charophyta during the last four decades has set the trend for future micropalaeontological investigations in the country.

Foraminifera : Bhatia is credited with the pioneering work on the recent foraminifera from several localities in the west coast of India. His record of brackish water foraminifera *Pseudoeponides* from Late Holocene Marl deposits of the Indo-Gangetic Plain suggests the occurrence of brackish water lakes (Oligo-Mesohaline) in Late Quaternary times in the Indo-Gangetic Plains. Bhatia is also credited with a significant discovery of foraminifera from the marine Permian beds from Umaria, Manendragarh and other localities. His work on the study of variation in some smaller foraminifera is widely quoted in text books on micropalaeontology.

Ostracoda : Fresh water Late Neogene and Quaternary ostracodes from the Siwalik group in the Lesser Himalayas and the Karewa Formation in Kashmir have been well documented in several of his works. He has also described three new genera of marine ostracodes from Karwar on the west coast. Several species belonging to these three genera are now well documented from several localities in the Indo-Pacific region. He is also credited with the first record and illustrations of fresh water ostracodes from the Late Cretaceous Intertrappean beds of Peninsular India. This discovery of ostracodes which have affinities with similar ostracodes from China and Mongolia confirms the recent views on the Late Cretaceous age of the Intertrappean beds. An interesting record of predation by gastropod drills on Eocene ostracodes from Kutch in Western India has been made by Bhatia and his co-workers.

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Charophyta : In yet another group of microfossils in which Bhatia has made significant contribution are the fossil and recent charophytes. His work on this group includes the first comprehensive monographic work on the Neogene charophytic flora of the Siwalik Group and its biostratigraphic significance. Similarly, he has published comprehensive works on the charophytic flora of the Deccan Intertrappean beds with particular reference to their age implications and palaeogeographic significance. In a recent paper Bhatia and his co-workers have recorded the oldest representatives of the family Characeae–*Aclistochara* cf. *A jonesi* Peck—from the Kota formation of the Gondwana Group.

Stratigraphy : Bhatia's work in collaboration with N S Mathur on the discovery of pulmonate gastropods in the passage beds between the Subathu and Dagshai formation is widely quoted and confirms the conformable nature of the contact between the two formations. In a comprehensive review, which has a bearing on the stratigraphy of the Early Paleogene sediments of the Lesser Himalayas, Bhatia has discussed the Facies, Fauna and Flora of the Subathu Formation. The discovery of a new Aptian—Albian horizon in the South Indian Cretaceous—Dalmiapuram formation with its age diagnostic ostracode fauna is recorded by Bhatia and Jain. In a widely quoted paper Bhatia discusses the various aspects of the controversial problem relating to the Tal Tangle.

Palaeozoogeography and Palaeoclimatology : Discovery and description of Quaternary fresh water ostracodes and Sub-recent marls of the Indo-Gangetic Plains by Bhatia have led to a better understanding of the Palaeozoogeographic implications of the ostracode fauna. Similarly, the first ever record of the discovery of a brackish water foraminifer—*Pseudoeponides* along with a brackish water ostracode *Cyprideis torosa* and the brackish water charophyte *Lamprothamnium* from the Late Quaternary marls of Haryana by Bhatia and Neena Singh suggest the occurrence of extensive brackish water lakes in parts of Haryana and throw significant light on Middle Holocene Palaeoclimatic and Palaeoenvironmental events in parts of Northern India.

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V L S Bhimasankaram

Bhimasankaram's contributions to geophysics have been essentially in two directions, viz. gaining knowledge of the earth, and in exploration of minerals, oil and gas and other subsurface economic deposits. These can be summarized under the following heads: (1) paleomagnetism and rock magnetism, and (2) geophysical prospecting technology.

Paleomagnetism and rock magnetism

Having been initiated in paleomagnetism and rock magnetism in the laboratory of P M S Blackett, at the Imperial College, London, Bhimasankaram has studied a large number of Indian rocks, in particular the Deccan Traps, for their paleomagnetism[1,2]. This study led to the establishment of the history of the geomagnetic field through Deccan Trap volcanism, and location of horizons of geomagnetic field inversions. The results further supported the theory that the earth's magnetic field reverses itself every few million years.

Bhimasankaram has also studied in detail the magnetic properties of natural and artificial pyrrhotites and has established the possibility of partial magnetic self-reversal in pyrrhotite in the laboratory due to electrostatic interaction of two magnetic components with differing curie temperatures. The work is of great significance in the context of attempts of geophysicists in demonstrating magnetic self-reversals in the laboratory[3,4].

Geophysical prospecting techniques

In exploration geophysics, one studies, with appropriate physical instruments, the spatial variations in some particular physical field or parameter associated with the subsurface under investigation. The presence of inhomogeneities, such as ore deposits, structures containing oil and gas, etc., causes deviations in the field measured from that one would expect if these inhomogeneities were not present.

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These deviations, termed as geophysical anomalies, form diagnostic indicators, and are interpreted in terms of the location, size, shape, depth, etc., of the causative body. On the basis of the physical field or parameter measured, there are several groups of methods in exploration geophysics, such as gravitational, magnetic, electrical, electro-magnetic, seismic, radiometric, geothermal, etc., each of which has a number of variants.

Bhimasankaram's contributions to geophysical technology have been in different directions: (i) development of methodology and applications, (ii) development of geophysical methods, (iii) development of laboratory and field equipment, (iv) theoretical and practical approaches in inversion problems of interpretation, and (v) the necessity of an integrated geophysical strategy for exploration of mineral deposits.

(i) Bhimasankaram has been responsible for the development of geophysical methodology for locating ground water in different geological terrains, such as hard rocks, sedimentary rocks and alluvial regions, and has thus contributed to the growth of the new subject of groundwater geophysics.

He has studied in detail the magnetic properties of manganese ores and has shown that within a short range of nonstoichiometric compounds between hausmannite and magnetite, the magnetic properties vary in a complicated manner. These findings were useful in explaining the complex field magnetic anomalies over manganese deposits[5,6].

(ii) Bhimasankaram has contributed significantly to the development of a geophysical method called piezoelectric method. The method involves utilization of the piezoelectric property contrasts between the causative body (quartz or pegmatite body) and the surrounding and overlying rocks. Here, an elastic impulse is produced in the ground and the electrical field developed along the profile is investigated. Bhimasankaram and his colleagues studied the piezoelectric properties of a few representative rocks and showed the possibility of using this method for locating hidden quartz and pegmatite veins, which sometimes contain valuable and strategic minerals[7].

(iii) Bhimasankaram and his colleagues have developed a few important geophysical field and laboratory techniques and equipment. Mention may be made of the following:

(a) A ground version of the transient electromagnetic survey technique was developed and introduced in the country by Bhimasankaram and his colleagues[8].

(b) Using indigenously produced proportional counter, an XRF analyser was developed and the methodology of analysis of some important ores was worked out. For the first time in the country, gamma-ray transmission and scatter technique have been developed for the rapid and non-destructive determination of ash content in coals[9].

The current research work is directed at field application of radon surveys in uranium exploration and development of nuclear geophysical methods for on-line field studies for evaluation of mineral deposits.

(c) Bhimasankaram and his colleagues developed a dipole induction profiling equipment (with focussing), useful for studying the apparent resistivity of the ground. A specific feature of this equipment is the possibility of reducing the influence of the top layer of the earth (where minor geological inhomogeneities cause noises) and to focus the study to an intermediate level. The equipment was found useful for groundwater studies in granitic terrain.

(d) Bhimasankaram was responsible for routine employment of geophysical logging techniques in ground water exploration and exploitation. He, along with his colleagues, developed indigenously a shallow borehole logging equipment (with complex measuring devices) which has been found to be very useful in ground water and mineral studies up to about 100 m depth.

(iv) The ultimate objectives of geophysical exploration activity being the location of economic subsurface deposits, inversion of the measured geophysical anomalies in terms of geological inhomogeneities assumes great significance. Bhimasankaram has contributed to the geophysical inversion theory in the following directions:

(a) He and his co-workers developed mathematical-statistical inversion techniques of inter-profile correlation and auto-correlation[10].

(b) Using Fourier transforms, numerical methods were proposed for inversion of geophysical data due to a number of bodies, such as trapezoidal prisms, two-dimensional circular cylinders, isosceles triangular bodies, inclined dykes, etc[11,12].

(c) He and his colleagues developed algorithms for ground water basins for use in microprocessors

(d) He and his colleagues solved direct and inverse problems of transient pulse induction method of prospecting for bodies such as two-layer earth, high conductivity overburden, etc[13,14].

(e) Since each of the geophysical methods is applicable in a particular physico-geological environment, and hence has its own limitations, the success of geophysical prospecting can be enhanced by utilizing a rational complex of different geophysical techniques. Bhimasankaram has put forth this idea strongly and pointed out the necessity of developing integrated geophysical inversion technology, through a series of lectures and publications[15].

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Guy Bomford

Elected as a fellow of the National Institute of Sciences of India (now Indian National Science Academy) in 1935, Bomford obtained his DSc from Oxford University. He was Royal Engineer (1921-48), seconded to the Survey of India (1921-48); Brigadier (1945-46); Reader in Survey and Geodesy (1948-66), Oxford; and Reader Emeritus (1966).

The studies conducted by Bomford were related mainly to the form of the geoid, initially in India, and later in Asia, Europe and Africa.

Bomford is a member of the Royal Astronomical Society, Geological Society (London) and Royal Institution of Chartered Surveyors. He was President, International Association of Geodesy (1963-67); and President d'honneur, International Association of Geodesy (1967); and Honorary Member, RICS. He was awarded the Order of the British Empire in 1946.

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Mihir Kumar Bose

Outstanding contributions have been made by Bose in the areas of petrology, mineralogy and geochemistry. Bose has also made some pioneering studies on the evolution of the Singhbhum Precambrian basin. His scientific contributions mark a new trend and outlook in the studies of Indian igneous rocks. Bose was one of those during the fifties who coupled detailed mineralogical and geochemical studies with analyses of structural geometry of several magnetic emplacements in this country. At the same time Bose remoulded the classical petrographic approach by adopting sophisticated methodologies for mineralogical and geochemical studies. He has enriched the scientific literature with wealth of data on mineralogy and geochemistry of igneous rocks—particularly alkaline rocks of India.

Bose was initiated to hard rock geology by S Ray at the Geology Department, Presidency College, Calcutta during the mid-fifties of this century. Later, he received inspiration for modern researches in mineralogy and geochemistry from T F W Barth at the University of Oslo, Norway, where he was a post-doctoral fellow during 1966-67. Bose's important contributions are summarised below.

Ultramafic rocks

Bose carried out detailed petrological and geochemical studies on ultramafic intrusions of Singhbhum. Strongly depleted ultramafic emplacements (of possible direct mantle derivation) were discriminated on the basis of trace element characteristics, from ultramafic intrusions cogenetic with the Newer dolerites. Bose has also studied the phase petrology of unusual garnet-pyroxenites from granulite terrain of south India. These assemblages are demonstrated to be transitional between granulite and eclogite facies metamorphism of supracrustal rocks.

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Alkaline emplacements

Based on intensive field and laboratory studies Bose presented a very detailed account on magmatic evolution of Koraput alkaline suite of Orissa. Gradually, he extended his studies to some other major alkaline complexes of the country, viz. Sivamalai suite of Tamil Nadu, Kunavaram and Elchuru plutons of Andhra Pradesh, Mound Girnar complex of Gujarat and Mer-Mundwara plugs of Rajasthan. These pioneering studies enabled Bose to publish significant amount of data on chemical petrology, crystal chemistry and differentiation history of a large number of alkaline complexes of this country. Comparative geochemistry of the alkaline complexes of the Eastern Ghat Belt has demonstrated the utility of inter-element correlation. As a leading expert on alkaline rocks Bose chaired a symposium on alkaline rocks at the 24th International Geological Congress (1972) held at Montreal. He also actively served the Subcommission on systematics and nomenclature of igneous rocks instituted by IUGS and was present in its Montreal meeting (1972) as Indian representative.

Anorthosite complexes

Bose has evaluated the magmato-tectonic history in the Eastern Ghats Precambrian belt and has attempted to establish a probable "event stratigraphy". Detailed structural and petrological studies have been done on anorthosites and mafic layered complexes of Kondapalli, Chimakurti and Chimal Pahad in Andhra Pradesh and Kadavur complex of Tamil Nadu. Comprehensive mineralogical and geochemical studies have brought out the stratigraphic crystallisation of the Kodapalli igneous complex. Computer aided geochemical modelling has quantified the differentiation history of this magmatic suite. High calcic anorthosite complex of Chimal Pahad in an envelope of medium grade metamorphics with imprints of polyphase deformation offer clues to possible Archaean even among pervasive Proterozoic imprint on the Eastern Ghats belt.

Mineralogy

Mineralogical contributions by Bose are varied and intriguing. Some major areas of investigations are : Chemistry and structural states of plagioclase and alkali feldspars from igneous complexes, demonstration of perthite as a possible indicator of Subsolvus temperature, crystal chemistry of nepheline in alkaline complexes, compositional trend of amphibole accompanying magma fractionation, textural evolution of Fe-Ti oxide minerals, origin of striped pyroxene in Sivamalai complex and phase relations of mafic silicates in ecologitic assemblages of south India.

Deccan volcanic province

Bose's studies on volcanic associations of Deccan province embrace detailed petrological studies on plug-like bodies of Mount Girnar and Mer-Mundwara and tectonic interpretation for alkaline magmatism in western India. Tectonic framework of the volcanic province has been evaluated in the light of plate tectonic concept and possible mantle plume activity has been identified. Rare alkaline ultramafic rock in association with carbonatite from Mer-Mundwara in Rajasthan has been studied and divergence in magmatic evolution has been worked out.

Singhbhum Basin

In recent years Bose has made pioneering studies on the tectonic lineage and sedimentation history of the Proterozoic Singhbhum basin. He has unravelled the history of a fossil marginal basin evolved in a back-arc tectonic setting. The role of extensional tectonics in basin evolution has been worked out through integrated petrological and geochemical investigations. The Archaean-Proterozoic boundary has been evaluated from a new perspective with emphasis on geochemical characteristics of Dalma volcanics and associated cover sediments in the basin.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Prosad Kumar Das

Das has made important contributions in several areas of atmospheric physics, especially on modelling different facets of the tropical atmosphere. His main areas of research were concerned with : (i) cloud physics, (ii) the dynamics of the Indian summer monsoon, (iii) the flow of air past orographic barriers, (iv) atmospheric pollution, (v) the mechanics of storm surges and (vi) the changes in relative sealevel over India. A brief account of his work is provided below :

Cloud physics

Prior to the Second World War it was widely believed that the origin of all forms of precipitation was at altitudes above the freezing point of water in the atmosphere. This implied that the change in phase from vapour to liquid water was relatively unimportant, because most raindrops were assumed to have their origin as ice crystals in the upper reaches of the atmosphere. This view was rapidly changed with the discovery that, in the tropics, rain was observed from clouds that did not reach the freezing level. A research group was formed at the Imperial College in London just after the war to investigate if the coalescence of drops could be a viable mechanism in place of the earlier concept of phase transformation from water vapour to liquid drops or ice crystals. Das was associated with this group. He was one of the earliest to work out the collection efficiency of spherical drops of different sizes. He computed the flow of air past spheres at low Reynolds number (*Re*) and worked out, numerically, what would be the percentage of small drops that could be swept up by a large drop falling under gravity. His computations were an improvement on earlier work, because he considered both the size of a large falling drop and the smaller colliding drops. Earlier work in this field had ignored the size of the smaller drops.

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Das later extended his computations to evaluate the change in the spectrum of drops in a rain cloud. He was able to demonstrate that the collision-coalescence process could be an effective mechanism for rain formation in the tropics. Previous research in this area had assumed a constant value of the collection efficiency, while evaluating the change in the spectrum of drops. This led to unrealistic results.

Monsoon dynamics

The first work on numerical weather prediction in India was initiated by Das. In collaboration with B L Bose of the Indian Meteorological Department he computed the path of a monsoon depression by using the conservation principle for vorticity in the atmosphere.

Subsequently, working in collaboration with Norman Phillips at the Massachusetts Institute of Technology from 1958 to 1960 in the United States, Das designed a three-dimensional model of the Indian summer monsoon, and worked out the distribution of heat sources and sinks that would lead to a steady monsoon. The model was based on the conservation principles for momentum and entropy in atmospheric motion. An important result that emerged from this study was the existence of a zone of rising motion over northeast India followed by subsidence or downward motion of air over northwest India. As subsidence implied the movement of air from lower to higher pressure or compressional warming, so to maintain a steady state the air over northwest India had to be cooled. The computed cooling was found to be approximately 2°C per day. A detailed study of the radiative balance over Rajasthan suggested that back-scattering of short wave solar radiation by a heavy dust load over Rajasthan could provide a cooling rate of the correct magnitude.

The work on heat sources and sinks was later extended by Das and M L Julka to study the vertical propagation of waves generated by a stationary heat source. Considering normal profiles of temperature and humidity in the atmosphere, the energy that was propagated vertically from a stationary heat source was analytically computed by a linear model. The vertical transfer of energy was worked out for a heat source of different dimensions.

The flow of air past orographic barriers

Continuing his research on different forms of forced motion, such as, the flow generated by heat sources, Das extended his work to study the motion forced by a large circular barrier. The dimensions of the circular barrier considered by him were large, which made it necessary to consider the latitudinal variation of the

coriolis force. The analytical treatment was based on linear perturbations imposed on a mean flow. It yielded interesting results on the formation of a trough to the lee of the circular barrier.

An extension of this work by Das and H S Bedi[10] showed how a mountain barrier in the form of the Himalayas could force monsoon depressions in the Bay of Bengal to follow a more westward track. In the absence of the Himalayan barrier their tract would have been more towards the north.

The model developed by Das and Bedi[10] had a coarser vertical resolution than the earlier three-dimensional model for the study of heat sources and sinks. But, the resolution was sufficient to indicate the broad features of the monsoonal circulation over India, especially the presence of an elongated trough running in an east-west direction parallel to the Sub-Himalayan mountains. The axis of this monsoonal trough was found to be sensitive to the reflective power (albedo) of the earth's surface. Even a small change in the albedo caused by rainfall could alter its position. This provided a qualitative explanation for "breaks" in the monsoon. During a "break", the belt of heavy rains suddenly shifted from the plains of India to northeastern India near the Himalayan foothills. This was accompanied by a rapid northward movement of the monsoon trough.

Atmospheric pollution

Around 1975 the location of a petroleum refinery near the city of Mathura in north India had become a matter of controversy. There were apprehensions about the emission of pollutants, especially aerosols and sulphur dioxide, which might damage the Taj Mahal located near Agra. A high-level committee was formed to ascertain the danger of emissions from the Mathura refinery. By numerically solving a diffusion equation for the dispersal of pollutants under realistic meteorological conditions, Das computed the lateral spread of pollutants from the Mathura refinery. The general conclusion was that the Taj Mahal will not be seriously endangered by the Mathura refinery. His model of atmospheric diffusion was accepted by the Committee appointed for this purpose. This was one of the earliest studies on atmospheric diffusion in India.

A similar study was made by Das to ascertain if the spread of soot particles and other gaseous pollutants released by the recent Gulf war would affect the Indian monsoon. By considering the vertical distribution of soot particles for different emission rates from the oil wells of Kuwait, and their horizontal speed of propagation, it was possible to show that the summer monsoon would not be affected. This conclusion was later substantiated by the turn of events following

the Gulf war. It was also supported by computations with a General Circulation Model (GCM) in other parts of the world.

The dynamics of the atmospheric boundary layer has an important bearing on the spread of pollution. In collaboration with a research group at the National Physical Laboratory (NPL) at New Delhi, a detailed study was made on the structure of the atmospheric boundary layer over Antarctica. The results provided an insight into the dynamics of the boundary layer over the Indian stations at Dakshin Gangotri and Maitri in Antarctica.

Storm surges

Following a devastating tropical cyclone which struck the coastal areas of Bangla Desh on November 12-13, 1970, Das initiated a study of storm surges that strike the Indian coast every year, mainly during the post-monsoon months. A numerical model was developed by Das with his colleagues in the Meteorological Department of India. The model computed the rise in sealevel due to forcing by the winds associated with a tropical cyclone. This is a storm surge. It is a gravity wave whose amplitude can be found by solving the shallow water equations in fluid mechanics. The main problems arise on account of an irregular coastline and a complicated profile of the seabed. In addition, the winds generated by a tropical cyclone are not symmetric. Consequently, there are considerable uncertainties about the frictional stress exerted by (1) the sea on the overlying wind and (2) by the seabed on the surge. Despite these difficulties, Das designed a model in which the coastal boundaries were represented by a series of steps in the form of a staircase. The winds generated by the cyclone were derived by satellite derived clouds as the storm approached the coast. Another feature of the model was the use of grid with high resolution near the coast, but merged with a grid of comparatively coarse resolution as one moved away from the coastal regions. A simple boundary condition was employed on the open sea, which provided for no inflow or outflow of energy from the region under consideration. Experiments with other forms of open boundary conditions had revealed that, if the open boundary was located at a large distance away from the coast, then the simple constraint of no inflow or outflow was adequate.

The results of the model were encouraging. The maximum surge for the cyclone at Chittagong in Bangla Desh was computed to be 3.2 m, which was of the right order of magnitude. Subsequently, this work was extended to cover cyclonic storms of different intensity striking different sectors of the Indian coast. The model outputs were used to prepare nomograms, which were useful for providing real time warnings to the coastal population. Subsequently, different

groups in India have experimented with other forms of coastal representation and different boundary conditions, but the first modelling effort was by Das and his colleagues in the Indian Meteorological Department. This work has been quoted in recent literature on storm surges.

Changes in relative sealevel

Considerable interest is now shown on sealevel rise, especially because it is related to climate change. The principal factors that lead to changes in sealevel are : (a) various land movements brought about by sedimentation and human activities, (b) changes in the level of seabed due to tectonic processes, (c) melting of land ice but not floating ice and (d) the thermal expansion of water brought about by global warming. The records of tide-gauges represent a net change due to both land movements and changes in sealevel due to thermal expansion of water. They are consequently referred to as the relative sealevel.

There have been statistical studies on changes in relative sealevel. The tide-gauge records suggest changes varying from 3.0 mm/yr to somewhere between 1.0 to 2.0 mm/yr. Some stations have even recorded a fall in sealevel.

Several sources of uncertainties exist in these estimates. Some stations have a data-set covering a limited period. There have been changes also in the location of tide-gauges. To overcome the latter, a data bank has been created by the Permanent Mean Sea Level (PMSL) by the International Council of Scientific Unions (ICSU) at the Bidston Observatory in the United Kingdom. The main data set has been reduced to a standard Revised Local Reference (RLR) which removes to some extent the ambiguities generated by a change in the location of a tide-gauge station.

To examine the possibility of a relation between relative sealevel and climate change Das, in collaboration with M Radhakrishna of the Department of Ocean Development, examined the tide-gauge records of all Indian stations. In the initial stages the records of only 4 Indian stations were used, with the data provided by the Survey of India. Later the analysis was repeated with RLR data from the Permanent Mean Sea Level data-set. The analysis revealed little evidence of a monotonic trend at all Indian stations. Only 5 out of 8 principal tide-gauge records revealed evidence of a trend. The mean trend was 2.5 mm/yr with a standard error of 7 mm/yr. If tectonic processes were partially taken into account then the mean trend was 28 mm/yr. The largest trend was observed at Diamond Harbour near Calcutta, which had only a record spanning 22 years. This was also in a region of heavy sedimentation and a high frequency of storm surges.

The trends were only visible from 1940 onwards for Bombay which, surprisingly, showed a falling trend for relative sealevel. Bombay is one of the few stations in the world which has a record exceeding 100 years. The trends at other stations were only visible from 1950 onwards.

There were indications to suggest other signals in the Indian tide-gauge records. Thus, there was evidence to suggest a pole tide with a 14 month periodicity. The amplitude of this tidal oscillation was considerably larger than the amplitude of the equilibrium tide (3 mm). This study is in progress. Interestingly no close relation was found between fluctuations in relative mean sea level and monthly rainfall at Bombay. The study has been briefly referred to in a booklet on *Meteorology and the transfer of technology* by the World Meteorological Organisation (WMO) in 1993.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Balakakrishna Ganesh Deshpande

Deshpande started his career at the Geological Survey of India (GSI) at Calcutta, got training at Assam Oil Company at Digboi and then was Petroleum Geologist at the Oil and Natural Gas Commission (ONGC). Subsequently in Indian Bureau of Mines he established laboratories for mineral beneficiation and mineral processing. He was professor and head of Department of Geology, Poona University till 1976.

Deshpande was a Professor in the Geology Department, University of Dar-es-Salaam, Tanzania. Besides being a Professor of Geology, he was a Consultant to the Government of Tanzania in geological matters, especially in groundwater, engineering geology and petroleum exploration. Realising the need of a local source of water, Deshpande explored for ground water and established two tube-wells which relieved the women's drudgery of fetching drinking water daily from long distances to a large extent. The wells are even to this day serving local needs.

On return from Tanzania Deshpande remained in the field of geology in its various branches like petroleum and gas and groundwater and later in earthquakes and amelioration in case of catastrophe. He devoted all his time, after 1982, to studying these subjects, giving lectures, writing scientific papers and also writing books and articles on the subjects of geology, earthquakes and environment.

Deshpande developed a hypothetical mathematical treatment in 1969, for a very complicated scientific approach, required for the exploration techniques of sub-surface structures leading to the discovery of oil.

The 'mathematical strategy' made a rather bold proposition that the search for selection of areas (structures) for drilling, involved tremendous scientific work and eventually, taking a plunge into drilling a well, which was then as even now, a veritable gamble. Deshpande proposed that with all the knowledge available

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then if we had intelligently made a grip on the ground, and drilled at intervals of some 20 kilometers, we could have struck some of the oil structures which we found years later.

While in Dar-es-Salaam (1977-1982), Deshpande had an opportunity to study in Kenya several unique geological structures like Kilimanjaro, Manyara and others as well as to observe the world famous animal behaviour, in response to the climate and the geological conditions there, as also in the north. The migration phenomenon of the animals there is unique, and a large number of tourists visit the northern parts of Tanzania and the southern part of Kenya, to observe the bio-physical phenomena of migration. Deshpande was deeply influenced by this phenomenon and was reminded of a similar behaviour of animals in response to the geological stimuli, especially the earthquakes and volcanoes.

Deshpande pursued the subject with particular reference to earthquakes. He was already involved in the examination of two earthquakes on the Makran Coast in 1945, where four new islands had emerged by the buckling of the sea floor. A thorough investigation was sponsored by the then British Government with substantial help from London. Several new facets of earthquake phenomena were observed by the team of the Geological Survey of India.

The next earthquake site Deshpande visited, participating actively in its study, was the one at Koyna in December 1967. There were several episodes of smaller earthquakes connected with Koyna Dam. In 1989 a bold astrologer predicted that Koyna would be rocked by a severe earthquake in the first fortnight of August, 1989. Having satisfied himself that seismologically there were no indications of an on-coming earthquake, Deshpande visited the Koyna area, during the relevant period, and explained to the people that scientifically there was no possibility of any earthquake then. There was no earthquake of any magnitude during the period. This episode emphasises the need to popularise the known scientific causes of earthquakes which are connected with the internal structure of the earth and the movements that go on at the junction of plates, etc.

Deshpande then decided to intensify his efforts to help society in reducing the risk of earthquakes by several well known do's and don'ts before and during an earthquake. Modern literature on the subject is replete with suggestions as to what people can do before and during the earthquakes, so that the damage to life and property may be reduced to the minimum.

In a book Deshpande pursued this subject vigorously, with the sole aim of bringing the geological and seismological aspects to the notice of the general public, starting with the most vulnerable areas and finally reaching even the apparently least vulnerable areas. Seismology, is still in a groping, empirical stage, in many respects. Accurate prediction is not yet possible for any scientific organisation in the world, and hence very little can be said authentically about earthquakes in general and their prediction in particular. The earthquake zoning map of India (1984), published by the Indian Standards Institutions, needs to be updated with experience of fresh earthquakes. Deshpande visited the areas affected by the earthquake of M 4.5, at Killari and Ausa in Latur District of Maharashtra. The affected area is at the very centre of zone I, which is supposed to be least susceptible to earthquakes. He has suggested, to the Indian Standard Institution, to take cognisance of this earthquake of October 1992. Even though there were no deaths or serious injury, numerous walls of houses are badly cracked and are now vulnerable to small earthquakes or climatic vagaries.

Deshpande was granted a project by the Department of Science and Technology for one year, for lecturing to volunteers in Assam to educate the rural populations, as to what precautions they should take before an earthquake to minimise their losses. Despite difficult social conditions with insurgents, he visited about 15 towns and environs, all over the state, and delivered some 50 lectures in the universities, colleges, schools, women's organisations, voluntary organisations like homeguards, Rotary, the Boy Scouts and Girl Guides, etc. About 10,000 people heard him. He showed about 30 transparencies and provided coloured posters of the size 30 cm x 40 cm which were exhibited before, during and after the lectures.

He delivered similar lectures in February 1991 at the GEOSAS-I International Conference held in Islamabad, Pakistan. Deshpande is now ready with the script of a book, '*You can survive an earthquake*' in which he emphasises the arrangement of the household, what precautions should be taken with regard to fire-fighting, provisioning of food in case the earthquake keeps the people out of houses for days together, how children can help the old and the infirm in the house to get out safely, how it is unwise to keep heavy loose objects above the head-level, how to tidy up their old unengineered houses, and several others.

Deshpande believes that earth sciences, as of today, are doing precious little to educate people and provide them with a scientific approach to the problem of

safety and not be perturbed, for instance, by an astrologer's prediction, disrupting the peace and tranquility of the society.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Abani Kumar Dey

Dey has worked in all major branches of geology from extra-terrestrial bodies like meteorites to most of the terrestrial materials.

The Valudavur meteorite

Dey conducted extensive studies[1] on this meteorite which fell in a paddy field at Valudavur, 10 miles north-west of Pondicherry on 30 October 1944. In appearance and chemical composition, the meteorite was shown to resemble the Kroonstad (Cronstadt) meteorite falling under group II of G T Prior's classification.

Rock types of the Eastern Ghats

The khondalite suite of sedimentary rocks and associated charnockites are the main types of the Eastern Ghats in India. These rocks exhibit every variety of structure and texture, and grade imperceptibly to garnetiferous sillimanite-bearing schists and gneisses through rocks that appear to be distinctly granitic. The work of Dey[2] has provided some support to J A Dunn's concept of diabrochomorphism (diabrochos = to soak, to permeate, to saturate or to wet).

Gold deposits

On two occasions (1935-1939 and 1967-72), in connection with projects sponsored by the Council of Scientific and Industrial Research, Dey worked in Jashpur, now in the Raigarh district of Madhya Pradesh, where gold occurs in the area lying south of Lat 22°39′ in the drainage basin of the river Ib and its tributaries[3]. Dey traced the source of gold to quartz veins traversing the gneissose granite country rock.

During 1970-71, an area of 3 sq miles between Barjor and Hatigara near Tangargaon was prospected for gold in quartz veins by the Directorate of

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Geology and Mining of Madhya Pradesh under the supervision of Dey and gold values assaying from 0.1 to 0.3 g/m tonne were found.

Buchanan's laterite of malabar

Opinion has been expressed that the term laterite should be used in the original sense, namely, for materials of the type described by Buchanan, and quarried at Angadipuram in Malabar for use as a building stone. Buchanan coined the term laterite to denote the physical property of being readily shaped into bricks and blocks when freshly quarried. The chemical composition is not strictly relevant, the type locality being very important. Dey did have the chemical analysis of representative samples of laterite collected with a view to studying the composition of the summit material *vis-a-vis* the softer vermicular below[5]. On the whole, it has been found that the top pellety layer from Malabar is definitely more laterized than the softer vermicular material below, but even then laterization is not complete in the same sense as for the laterites of the Deccan trap. If Fermor's terminology is accepted, none of the samples of the lateritic material from Malabar represents 'fully formed' laterite.

$FeO(FeV)_2O_3$, a new vanadium-bearing mineral

This mineral, named Coulsonite by J A Dunn and Dey[6], was discovered near the southern borders of the Dhalbhum subdivision of Singhbhum, Bihar and extending into Mayurbhanj in Orissa. It has been found in many places in India, and abroad, for example, Ontario in Canada, New York State in USA, etc. The mineral is of strategic importance for making special steels. It occurs in very close association with basic and ultra-basic rocks, sometimes altered to serpentines, more often to epidiorite, but, as a rule, little changed from the original basic gabbro of which it is a magmatic segregation.

Miocene mollusca from Quilon, Kerala

Dey[7] found the fauna to show distinct affinities with those of the Gaj and Karikal beds of India, and several species to be identical with those of the Miocene and Pliocene of Java. There is hardly any doubt that this fauna is of the same age as that of the Miocene of Sri Lanka, since such species as *Taberina malabarica* (Carter) and some of the typical Gaj forms found in Quilon have also been recorded from Sri Lanka. But whereas in Quilon the individuals are dwarfed, in Sri Lanka they are thick, robust and full-grown. Vredenburg [*Rec Geol Surv India,* **55** (1923) 110-118] described these species of *Placenta,* viz. *P birmanica, P promensis* and *P sindiensis,* from the Miocene of India and Burma, which with a more or less developed pair of subsidiary ridges have an irregular platform

between the primary resilifier. For these he proposed the term *Indoplacuna,* constituting a new sub-genus of *Placenta.* Although the fossil from Quilon agrees well with *Indoplacuna* in having the platform between the resilifier ridges, it cannot be strictly included under that sub-genus in as much as it has no distinct secondary pair of resilifier ridges; moreover, the arched resilifier forms just less than a right angle. These features point to a further stage in the evolution of *Placenta* than had been reached by *Indoplacuna.*

Vrendenburg (*ibid,* p 110-118) considers *Indoplacuna* to be extinct, not having survived the Middle Miocene (*ibid,* p 117). The occurrence of *Placenta lamellate* (a form intermediate between *Indoplacuna* and *Placenta*), therefore, suggests that the Quilon limestone bed is younger than Middle Miocene.

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Vinod Kumar Gaur

Gaur's pioneering contributions to new knowledge in earth system science include: discovery of the host rock effect in geoelectromagnetics, seismotectonic setting of the Central Himalaya, discovery of a thick (more than 200 km) lithospheric root beneath the Dharwar craton using seismic tomography, and crustal strain field in south India using GPS constrained baselines.

Gaur's contributions to advancement of Indian scientific endeavours in Earth system sciences include years of painstaking design of academic programmes in geophysics in Indian universities, and later at NGRI (1983-88), where he introduced new incisive scientific programmes notably, isotope geochemistry, mineral physics, digital seismics and magnetotellurics and telemetered seismic networks, all backed by new powerful computing environment. As secretary to the Government of India (1989-92), he designed and implemented new modern programmes in Antarctic science, and a National Ocean Information System (NOIS), and established new operational programmes towards improving the quality of life and work of the people in our coastal areas notably, the Marine Satellite Information Service (MARSIS), Coastal Ocean Monitoring and Prediction Systems (COMAPS) as well as a network of cooperating institutions for researches on drugs from the sea, and for the design and development of productive Coastal Ocean System (CODAPS).

Landmark contributions

Four landmark contributions made over the past 30 years, which have created new knowledge and enriched our understanding of major earth processes and structure are as follows:

(a) Discovery of the host rock effect in geoelectromagnetics (1959-63) bringing to light an unexpected enhancement of the electromagnetic anomaly produced by a conducting geological body buried in a

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partially conducting (3 orders of magnitude less) host rock, and explanation of this then intriguing effect, which has stood the test of time; as well as detailed interpretational aids produced subsequently (1971-72) to exploration of buried geological conductors using model experiments quantitatively scaled in accordance with the principle of electrodynamic similitude.

(b) A direct test (1960-73) of the hypothesis that the Indian plate slips along the main boundary fault, and measurement of the slip rate (0.9 cm/yr) along one of its segments (Nahan Thrust) using a sensitive instrument (water tube tiltmeter) especially designed and developed for this purpose. Not only did this experiment unambiguously delineate the plate collision boundary in one of the most scientifically intriguing and socially important part of the globe, but also provided a model for the style and scale of kinematics of the Himalayan boundary of the Indian plate to illuminate rational approaches to earthquake hazard assessment in a region under increasing stress of human population and large scale river valley development projects.

(c) A slip model of the (northward moving) Indian plate in Kumaun Himalaya based on well constrained hypocentral locations (especially depth) and fault slip directions of local earthquake determined by a specially designed seismic network (1978-85), thereby providing a basic framework for earthquakes hazard assessment along the Himalaya generally and in the Kumaun (Garhwal) Himalaya in particular.

(d) Discovery of a thick (400 km) high velocity root of the Indian Lithosphere beneath the Deccan Volcanic Province (1985-89) as well as beneath most of the South Indian shield (1989) using delay time seismic tomography, with profound implications to the nature of the processes that created one of the largest outpourings of flood basalt on earth, essentially produced by ocean rifting that happened to overlie a mantle plume.

Indeed these results have the potential of illuminating a higher paradigm by which one may reinterpret the manifestations of unified earth processes which have created a range of prominent intriguing lithospheric features from Arachaean continental relics to newer ones on the still spreading Indian Ocean floor, bymodelling the physical consequence of a 400 km thick continental plate ploughing inexorably into the rest of Asia.

Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Subir Kumar Ghosh

Ghosh has worked on different aspects of structural geology. In the major part of his research he has combined critical field observations with experiments and theoretical analyses on the mechanics of development of geologic structures. The earliest of Ghosh's research involved the inter-relations between the structural history and the metamorphic-migmatitic history of the Precambrian rocks around Kuilapal, West Bengal. Ghosh's study showed that the progressive metamorphism was broadly synchronous with the late stage of folding of beds and was earlier than the development of the crenulation cleavage. This work suggests that although progressive metamorphism and migmatization are closely related in time and place, they do not have a cause-and-effect relationship at the level of observation.

Ghosh and his associates working in the Simla area of the Himalayas found that the present structures (schistosity and mineral lineation) and the metamorphic characters of the Jutogh mica schists had developed during the evolution of the Himalayas and were not relics of Precambrian structures and metamorphism. Ghosh and Naha initiated the macroscopic structural analysis of the Banded Gneissic Complex of Rajasthan from the structural geometry of map-scale metasedimentary enclaves in migmatites.

A systematic study of the mechanism of buckle folding started from the middle of the sixties, and Ghosh was one of a small group of persons who made a significant contribution on this topic. It was shown by Ghosh from experiments that the orientation of the *XY* plane of the local strain ellipsoid shows distinctly different patterns in buckle folded competent and incompetent layers similar to cleavage refraction or convergent and divergent cleavage fans. It was also shown that, in a layer oblique to the principal axes, the fold axis is initiated parallel to the long axis of the strain ellipse on the layer-surface. The buckling experiments on multilayers[2] showed that kinks and conjugate folds develop in those multilayers

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in which sliding between layers is inhibited. On the other hand, smoothly curved sinusoidal folds are generated if the inter-layer sliding is easy.

Ghosh had worked in the Scandinavian Caledonides in collaboration with Ramberg and others. In connection with field studies in the Hemmelvik-Hell region of Norway, Ghosh and Ramberg suggested that the neutral folds on subvertical enveloping surfaces developed by gravitational collapse. This study also showed that both layer-parallel homogeneous strain and layer-parallel shear strain are important to explain the pattern of cleavage refraction in layered rocks. Ghosh and others also analysed the history of superposed folding in relation to thrusting, metamorphism and migmatization in the Seve Nappe around Areskutan in the Swedish Caledonides.

A major contribution by Ghosh is in the field of interfering buckle folds. The theoretical studies[3] showed that the domes and basins which developed in a constructional deformation are somewhat larger than those which are produced by a unidirectional layer-parallel compression. He also considered the development of small second generation folds by axial compression of cylindrical first generation folds. The arc lengths of the smaller late folds are controlled by the curvature of the early folds. The buckle folds in a contractional deformation are characterized by arcuations and virgations and by association of domes and basins with diversely oriented folds. Superposed buckle folding in single layers[13] can take place in any one of four standard modes. The transition from one mode to another depends on the initial morphology of the early folds. These four standard modes of superposed buckling are modified in different ways in multilayers[14] of different types. The axes and axial surfaces of superposed folds on a thin stiff layer may show a much more complex pattern than those folds which develop on thicker and less stiff layers. Unlike the model of shear folding, buckling of tight or isoclinal early folds cannot give rise to a type 1 pattern. A remarkable feature of the experiments was the recognition of the process of hinge replacement, in which the hinge of the early fold was completely obliterated and was replaced by a newly formed sinuous hinge similar in appearance to the curved hinge lines of early folds in a type 2 interference. Ghosh's work on structures produced during rotation of rigid inclusions[4-7] is often cited and has stimulated a number of later researches on this topic. These theoretical and experimental studies showed how a variety of drag patterns of a passively behaving foliation can develop around the inclusions under pure shear, simple shear and by more complex types of plane strain. The experiments with bulk simple shear produced an unusual kind of drag

pattern, which was later discovered in natural rocks by Bell and others and was described as millipede structure.

The foliation in the groundmass may continue to track the *XY* plane in progressive noncoaxial deformation, or may deviate from it and rotate as a passive marker. It was shown that this deviation cannot exceed 5.15 and is generally much smaller[5]. However, even with such a small deviation, a large shear strain may develop along the foliation[8]. The frequently cited paper by Ghosh and Ramberg[6] derives for the two-dimensional case the equations for the rates of rotation and finite rotation of rigid ellipsoidal inclusions in different kinds of plane strain. If the bulk flow has a kinematical vorticity number (W_k) of less than 1, a rigid ellipsoidal inclusion may not rotate indefinitely but may attain a stable orientation. This stable position is dependent on W_k and the aspect ratio of the inclusion. Under certain situations the inclusion may rotate backward. The difference between the rates of rotation of a passive marker plane and a rigid ellipsoidal inclusion becomes negligibly small when the aspect ratio is greater than 5. These general principles have been applied to interpret different types of structures, e.g. rotation of porphyroclasts, development of different types of inclusion trails within porphyroclasts, an echelon arrangement of boudins and drag patterns of foliation around rigidly rotating geologic bodies. Experimental and theoretical studies on both rigid and deformable inclusions were carried out by Ghosh and Sengupta to interpret certain features associated with deformation of conglomerates[4]. Ghosh has also suggested a method to measure the degree of noncoaxiality[10] in rocks under certain situations.

Ghosh and Sengupta made detailed investigations in the progressive evolution of structures in ductile shear zones[11] in the Singhbhum Shear Zone and in Kolar. The Singhbhum Shear Zone shows a fairly wide belt of structures transitional between those of the shear zone proper and the northern fold belt. Folds in the shear zone were repeatedly initiated and were rotated to a nearly reclined attitude. The early buckle folds with gentle curved hinges were deformed at a later stage to sheath folds. The mylonitic foliation and lineation were repeatedly transposed in a single continuous deformation.

An empirical model of simultaneous buckling and flattening was utilized to derive a variety of patterns of folded early lineations[9]. Under certain conditions a lineation is deformed in such a manner that when the fold is unrolled the lineation remains strongly curved in the shape of a U. Such a lineation pattern gives us significant information about the rotation history of folds.

Theoretical and experimental studies showed that chocolate tablet boudins with two sets of mutually perpendicular boudin axes may form in different ways[12]. In a general flattening type of deformation one set of extension fractures first forms perpendicular to the maximum tensile stress in the matrix. Once these long narrow boudins are formed, the maximum tensile stress in the brittle layer becomes approximately parallel to the long axes to the boudin. As a result a second set of fractures forms perpendicular to the first set. In lineated rocks the anisotropy of tensile strength leads to the sequential formation of two sets of extension fractures parallel and perpendicular to the lineation.

The tectonics of the Jharia coal basin was worked out in detail by Ghosh and Mukhopadhyaya. A geometrical analysis of soft sediment folds suggested that a sandstone bed was liquified or fluidized while the interlayered clay units were broken and contorted during slumping. When the downslope movement slowed down, the piled up mass of sand was flattened under its own load and the contortions of the clay phenoclasts acquired their recumbent character. In another study (by Ghosh and Lahiri) of soft sediment deformation structures the penecontemporaneous contortions of the Ghatsila Galudih area were interpreted as interpenetrative contortions. Similar structures were experimentally produced by vibration of freshly deposited sand clay layers.

Oceanic ridge transform patterns show certain geometrical peculiarities that any theory of transform faulting must explain. Similar patterns were experimentally reproduced when a thin film of wax, solidifying on the surface of molten wax were subjected to tension. It was suggested that the newly formed lithosphere in spreading zones develops mechanically weak planes that ultimately control the orientations of the transform faults.

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Kunchithapadam Gopalan

Introduced early on to the applications of physics to the solutions of fundamental geological problems Gopalan has specialized in the use of naturally occurring isotopic variations in key chemical elements as chronometers and tracers of terrestrial and extraterrestrial processes. Besides his significant scientific contributions, he has played a pivotal role in the development of modern isotopic researches in earth and planetary sciences in India.

Naturally occurring isotope variations of chemical elements result from either chemical or nuclear processes. Chemically induced isotope variability is the consequence of different isotopes of the same element having slight but distinct differences in their chemical properties like free energy of chemical reactions and reaction rates. Decay of long-lived radioactive parent isotopes into stable daughter products, and nuclear reactions such as induced by cosmic rays produce dramatic isotopic variations. Gopalan, in his nearly three decades of research, has used all these three sources of isotopic variability to characterize events or processes of evolutionary significance.

After getting his PhD in Physics from the Indian Institute of Science, Bangalore in 1966, Gopalan proceeded to the University of California, Los Angeles to work with G W Wetherill. There he took the technically challenging and scientifically front-ranking problem of the time of formation of chemically and hence genetically related suite of stony meteorites, which would give model-independent estimate of the age of the solar system itself. His pioneering work on hypersthene[1] and enstatite chondrites[2] clearly showed that planetary formation was a very sharp event about 4600 million years ago. He also demonstrated distinct isotopic disturbances relatable to very recent collisional heating, presumably in the asteroidal belt[3].

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Because of the special expertise he had developed in studying the scarce meteorites, Gopalan was one of the select band of scientists to study the first batch of moon samples in 1969. Even this very first study demonstrated that the moon was not still born, contrary to prevailing beliefs, but remained volcanically active for at least the first 1000 million years of its history[4].

Gopalan joined D Lal's group in the Tata Institute of Fundamental Research on his return to India in 1970 to initiate radiogenic isotope studies to complement the ongoing program on cosmic-ray produced isotopes. For this purpose, he built a highly sophisticated Reynold's type glass mass spectrometer the only design known at that time to detect the extremely tenuous amounts of noble gases of various origins in meteorites and moon samples. Working with M N Rao, he determined the residence time of stony meteorites as small planetary debris in the solar system[5], solar wind gases trapped in primitive meteorites and unshielded lunar soil grains[6] recovered by the American and Russian lunar missions. He also detected for the first time products of solar flare proton reactions with the silicate matrix of lunar soil[7].

When Gopalan moved to the Physical Research Laboratory, Ahmedabad in 1973, he switched from cosmo- to geochronology to reconstruct the major processes and schedule of events that shaped the geologic mosaic of the Indian subcontinent. For this purpose, he built his second mass spectrometer for isotopic measurements of radioactive rubidium and its daughter product, strontium to determine Rb-Sr ages of rocks and minerals. Though crude by present-day standards of mass spectrometric instrumentations, he used this machine to demonstrate for the first time the presence of Archean (> 2500 million years old) crustal relicts east of Udaipur in Rajasthan[8] and to infer that the landmass of Rajasthan is a fusion of two chronologically distinct continental blocks along the Aravalli mountain range. Since this home-made mass spectrometer was not adequate for the very high precision measurement of neodymium isotopic composition necessary to identify mantle sources of deep seated volcanism such as the vast Deccan volcanic province of central and western India, he collaborated with J D Macdougall of the Scripps Institution of Oceanography. This work showed that the voluminous lava extrusions were derived from partial melting not of a virgin upper mantle, but of one which has had a prior history of melting to yield crustal extracts[9]. Extending these studies later to the slightly older Rajmahal basaltic volcanism of eastern India, it was shown that the mantle sources of the Deccan and Rajmahal lavas were distinct isotopically[10].

Realising the need for other types of isotopic studies in the Indian context, Gopalan created two major isotope facilities—a stable isotope laboratory for very high precision measurements of the isotopic composition of hydrogen, carbon and oxygen, and a mass spectrometer for precise ^{39}Ar-^{40}Ar dating. Using the former, he and his student R Ramesh demonstrated that plant cellulose deposited as annual growth rings of trees shows coherent H, C and O isotope signals among trees growing in a region, which can be related to extant climatic parameters like temperature and precipitation[11].

Working with T R Venkatesan, Gopalan measured the precise age of extrusion of individual lava flows from the thick Deccan volcanic pile in the Western Ghats. These results clearly showed that the Deccan volcanism erupted not later than 67 myr ago and lasted for at least 4 myr. Both the timing and duration of the Deccan volcanism argue against Deccan volcanism as the cause of the major biological catastrophy recorded in the sediments across the Cretaceous Tertiary transition[12].

In 1984, Gopalan was invited to the National Geophysical Research Institute, Hyderabad to organise a world-class geochronology laboratory for the Indian scientists to use modern measurement techniques, observations and concepts to understand the evolution of major geological features of India. Focussing mainly on the classic south Indian crustal block, Gopalan and his coworkers have revealed isotopic evidence for large scale hydrothermal activity in the Dharwar supracrustal belts significantly later than their extrusion[13]. He has found that the structurally distinct components of the vast Peninsular Gneiss are also chronologically distinct, indicating the polyphase history of this complex[14].

Kimberlites are products of deep seated (< 100 km) magmatism and imply unusual mantle conditions for their eruption. So the wide range of ages previously reported for the diamondiferous kimberlites of south and central India was enigmatic, as it implied the extraordinary persistence of unusual mantle conditions beneath the Indian continent, unlike elsewhere in the world. This problem was recently solved by demonstrating sharply episodic kimberlite magmatism at 1090 ± 20 myr in both the regions[15]. The near contemporaneity of such magmatism over continental dimensions is a very significant finding in our effort to understand such deep seated phenomena. Gopalan has recently achieved precise neodymium isotope ratio measurements on par with the leading laboratories of the world—thereby opening yet another isotopic window for the Indian earth scientists to probe the mechanism and time schedule of material

transfer to the crust from the mantle, as recorded in the physically separate and chemically distinct rock bodies of the Indian subcontinent.

Gopalan believes that he has been able to take the Indian effort on isotope geology from where it was left by his mentor, the late V S Venkatasubramanian, who pioneered geochronology in India in 1953 when this science was at its infancy even globally.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Harsh Kumar Gupta

Gupta has been primarily working in applied geophysics with special emphasis on seismology. The following is a brief outline of his contributions:

Himalayan region : Gupta for the first time from a systematic analysis of surface wave dispersion provided convincing evidence[1] of an extremely thick (65-70 km) crust below the Himalaya and Tibet Plateau region in 1967. These findings were confirmed by other workers in the years to follow, particularly by the deep seismic sounding studies in the Tibet Plateau region carried out in 1980s by the Chinese and French scientists. Gupta also showed the existence of a shield-like upper mantle structure below the Indo-Gangetic plains.

Reservoir induced earthquakes : Gupta has carried out detailed investigations of the earthquakes associated with the artificial water reservoirs and delineated certain characteristics common to them. He also investigated natural earthquakes (not associated with reservoirs) of the concerned region and thereby generated criteria to discriminate the reservoir induced earthquakes from natural earthquakes[2]. These criteria are now applied internationally to understand the possible relationship between earthquakes occurring in the vicinity of reservoirs and the part played by the reservoirs in triggering them. He showed that small magnitude earthquakes (less than magnitude 3) could be caused through the settlement of the basement due to the water load. However, in case of large magnitude earthquakes, the reservoir provides only triggering effect in critically stressed strata through one or more of the three possible mechanisms, i.e. (a) change in effective pore pressure causing failure, (b) incremental stress due to water load causing failure, and (c) change in mechanical properties of rocks, making them less competent and thereby releasing the accumulated strain. This work formed the basis of the well known books *Dams and earthquakes*[3] and *Reservoir induced Earthquakes*[4]. There are over a dozen papers which have brought out several salient features of reservoir induced earthquakes, of which special mention may be made of Refs 1, 2, 5-7.

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A medium-term earthquake forecast : There is a global effort to recognize and establis.ı patterns that precede major earthquakes. An effort in this direction was made by Gupta and Singh[8] in the north-east India region. Encouraged by the discovery of a precursory swarm and quiescence preceding the Cachar earthquake of December 30, 1984, Gupta and Singh[8] carried out an in-depth study of all the earthquakes of magnitude greater than or equal to 7.5 since 1987 and several smaller magnitude earthquakes that occurred after 1962. In their study they discovered that the main shock magnitude (M_m) has correspondence with the magnitude to the largest events (M_p) in the swarm and the time interval (T_p) between the onset of swarm and the occurrence of main shock in days. Following are the relations found by them

$$M_m = 1.37\,M_p - 1.41 \text{ and } M_m = 3 \log T_p - 3.27$$

Gupta observed that it is important to recognize swarm and quiescence before the occurrence of the main shock. They discovered one such region in the vicinity of Indo-Burma border and concluded that—(1) moderate magnitude to great earthquakes in the north-east India region are found to be preceded, generally, by well defined earthquake swarms and quiescence periods, (2) on the basis of an earthquake swarm and quiescence period, an area bound by 21°N and 25.5°N latitudes and 93°E and 96°E longitude is identified to be the site of a possible future earthquake of M 8±0.5 with a focal depth of 100±40 km. This earthquake should occur any time from now onwards. Should it not occur till the end of 1990, this forecast could be considered as a false alarm.

It was pointed out that the annual frequency during the swarm period is several folds higher than the background seismicity and quiescence epochs[8]. The occurrence of August 6, 1988 earthquake with focal parameters mentioned in Table 1 has made this medium term forecast a success. This success encourages

Table 1 - Forecast of August 6, 1988 earthquake[8]

Earthquake	Forecast	Occurrence
Parameters	(Gupta and Singh[8])	NEIS (Preliminary determination)
Epicenter	21°N to 25.5°N 93°E to 96°E	25.149°N 95.127°E
Magnitude	8 ± 0.5	7.3
Depth	100 ± 40 km	90.5 km
Time	February 1986 to December 1986	August 6 1988 (00.36.26.9 G.C.T.)

one to make similar investigations elsewhere in the Himalayan Frontal Arc for concentrating hazard related investigations in a few critical areas.

Global studies on stress : Gupta along with several other workers, on a global basis, have conducted state-of-the-art studies on assessing the global pattern of intraplate stress[9]. As far as India is concerned, the state of stress has been investigated in three major provinces, namely the Himalayan, Peninsular India, and the Andaman and Nicobar regions. It is found that in Peninsular India and Andaman and Nicobar regions, orientation of $S(H_{max})$ are generally uniform and vary from NS to NNE and SSW in the Himalayan region. There is a significant change from NNW-SSE in the western syntax region to NNE-SSW and N-S over the frontal arc and almost E-W in the Arakan Burma Region.

Antarctica research : Gupta was the leader of the Third Indian Scientific Expedition to Antarctica, which successfully set-up the permanent research station, Dakshin Gangotri, during 1983-84 in a record time of one Antarctic summer. Laudable scientific work[10] on Antarctica has won India the coveted membership of Antarctic Treaty and Scientific Committee on Antarctic Research.

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Alok Krishna Gupta

Gupta started his research career at the University of Pittsburgh at Pennsylvania, USA, where he undertook his doctoral and postdoctoral studies (1965-1969, 1969-1971) on various problems related to the genesis of alkaline rocks under the guidance of E G Lidiak. He worked on different petrological problems at the University of Western Ontario (1971-1974), Ruhr University, Bochum, Germany (1974-1975); Hokkaido University, Sapporo, Japan (1975-1977); Melbourn University (1979-80) and University of Tasmania (1983): The colleagues with whom he made serious contribution in the field of petrology include, W S Fyfe, N D Chatterjee, Kenzo Yagi, John Lovering and D H Green. He has been working as a Professor and Head at the Department of Earth and Planetary Sciences, University of Allahabad, since July, 1985. This department has been founded by him.

Gupta has a strong background in petrology and has made substantial contribution in relation to the genesis of ultrapotassic volcanic rocks. His landmark contributions are summarized below.

Genesis of pseudoleucite

Leucite ($KAlSi_2O_6$) is a common mineral found in ultrapotassic lava, which occurs not only in all the continents but even in truly oceanic islands. Some of the well-known localities include, Roman province of Italy, Almaria province of Spain, East Eifel, Germany; Utsuryo Islands; Tritanda cunha Islands; Leucite hills of Wyoming, USA; Rift valley, Africa; Tezark Mt Kazaksthan, West Kimberley, Australia; etc. In older lavas pseudoleucite with icosi-tetrahedron structure like leucite is observed. Although its outer form is exactly like that of leucite, a thin section of the crystal shows that it is in effect an intergrowth of nepheline and feldspar, or made entirely of analcime $(Na,K)AlSi_2O_6.H_2O$.

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N L Bowen suggested their formation by reaction of leucite with alkalic liquid, as the latter reach the leucite- feldspar cotectic line and then to the eutectic in the nepheline-kalsilite-silica system. This would explain the assemblage and the intergrowth but not the outer form. Gupta took several leucite crystals from Reccomonfina, Italy; and did series of experiments involving leucite crystals and sea water. His experimental runs at 1 kbar for 1 day, 3 days and 7 days at 150°C with different leucite crystals showed systematic substitution of K by Na from sea water. Ultimately the major portion of the leucite crystal was converted to analcime [$(K,Na)AlSi_2O_6.H_2O$]. At slightly higher temperature [$Na,KAl]Si_2O_6.H_2O$ was not stable, but it yielded $(Na,K)AlSi_3O_8$ and $(Na,KAl)SiO_4$ (e.g. $2(Na,K)AlSi_2O_6.H_2O) \Leftrightarrow (Na,K)AlSiO_4 + (Na,K)AlSi_3O_8 + H_2O$. The outer form of leucite was retained but the intergrowth of $(Na,K)\ AlSiO_4 + (Na,K)AlSi_3O_8$ in one case and $(Na,K)AlSi_2O_6.H_2O$ could be explained. This model is now generally accepted by scientists from all over the world.

Synthesis of bicchulite

Henmi, a school girl from Japan was working on Skern rocks form Fukuoka, Japan. These rocks are produced by metamorphism of Al- and Si-rich limestone in contact with an intrusive igneous body. She found in her assemblage the presence of gehlenite ($Ca_2Al_2SiO_7$), grossularite ($Ca_3Al_2Si_3O_{12}$) and another unknown mineral, which was present only within gehlenite. This unknown mineral was too tiny to determine their chemistry by microprobe analyses, although its presence could be confirmed by X-ray. A group of English scientists, also confirmed her observation but could not establish its composition or structure.

Gupta synthesized gehlenite and subjected it to a water pressure of 1 kb for about a week. The X-ray pattern of the yield was similar to that of Henmi, i.e. intergrowth of grossularite, gehlenite and tiny crystals of this unknown mineral (bicchulite). He crushed the sample to fine powder, so that their will be microfractures within the gehlenite crystals and the tiny crystals could be exposed to the vapour phase. The crushed and the tiny crystals could be exposed to the vapour phase. The crushed samples were heated in presence of vapour pressure again at 750°C and one kbar for two weeks. The samples were crushed again and once again put inside the vessel, and the experiment was repeated under similar P-T condition. A single phase bicchulite could be formed after this procedure was repeated many times. The analyses showed that its composition is $Ca_2Al_2SiO_7.H_2O$. Its crystal structure and thermodynamic property was also

established by Gupta. An earlier attempt to synthesize bicchulite by American Bureau of Standards was not successful.

Genesis of kimberlite by subfraction of eclogite: A negative experiment

O'Hara and Yoder (1967) suggested that by partial melting of an ultramafic upper mantle, a MgO-rich picrite basalt can be formed by subfraction of eclogite at a depth of 100 km. Eclogite is a rock comprising omphacite [$CaMgSi_2O_6$ (diopside) and $NaAlSi_2O_6$ (jadeite) solid solution] and pyrope ($Mg_3Al_2Si_3O_{12}$).

According to them, this would produce a liquid which will be devoid of Ca,Al, Na and poor in silica. Gupta took a natural picritic basalt of known composition, crushed the sample and did series of experiments at 30 kb and different temperatures. Pyrope and omphacite crystal did appear in addition to oxides and liquid at 800°C and 850°C. Analyses of the liquid, however, showed that the liquid was a nephelinite, similar to that found in Hawaiian lavas or Rift Valleys throughout the world. D H Green and A E Ringwood suggested that subtraction of eclogite from a picrite liquid would yield a nephelinitic magma. The negative experiments of A K Gupta showed that the hypothesis of O'Hara and Yoder is not tenable.

Effect of silica concentration on the solubility of Ti and Al in pyroxene and its importance

Clinopyroxenes from silica-undersaturated igneous rocks differ mainly from silica oversaturated rocks in containing greater amounts of Al and Ti. The solubility of Ti in clinopyroxenes increase with the amount of Al present in tetrahedral sites.

Gupta investigated the effect of silica concentration on the solubility of Al and Ti in diopside pyroxenes at one atmosphere in the system diopside-$CaTiAl_2O_6$-SiO_2 at temperatures between 1150 and 1420°C. He established that the composition of pyroxene in the system diopside-$AcTiAl_2O_6$-SiO_2 is influenced by the total SiO_2 content. Near the join diopside-$CaTiAl_2O_6$, the pyroxene forms a solid solution with the $CaTiAl_2O_6$ molecules, which coexists with perovskite for compositions greater than 11 weight per cent, $CaTiAl_2O_6$. Anorthite is an accompanying phase. With increasing total SiO_2 content a series of mineralogical changes involving Ti-bearing phase occur. Sphere solid solution co-exist with diopside solid solution anorthite, and perovskite in a small compositional range near diopside-$CaTiAl_2O_6$ join. Additional total SiO_2 results in elimination perovskite and a decrease of solid solution in the pyroxenes, which is approximately pure diopside. Rutile joins diopside, anorthite, sphene solid solution and tridymite over a broad compositional range in the Ti-Si-rich part of

system. These results demonstrate that increased silica concentration decreases the solubility of Al and Ti in diopside pyroxene and controls the stability of co-existing Ti-bearing phases.

Leucite-5, Na-feldspar incompatibility

In leucite-bearing lavas the coexisting feldspar is either a Ca-rich plagioclase of a K-rich alkali feldspar or both. On thermochemical grounds, A Miyashiro postulated that the apparent incompatibility between leucite and albite may not exist at high temperatures. W S MacKenzie and S Rahman described veins of leucite and Na-feldspar in a basanite from a Mafssif Central, Frânce, but were unable to confirm this as a stable assemblage. In order to solve this controversy, Gupta studied the system leucite-albite at atmosphere. Phase relations at atmospheric pressure in the pseudobinary join $KAlSi_2O_6$ (Lc)-$NaAlSi_3O_8$(Ab) and in the pseudoternary join Lc-Ab-$CaAl_2O_8$(An) indicate that leucite is incompatible with Na-feldspar. In the former join leucite can exist with an alkali feldspar. In the Lc-Ab-An join, leucite only coexists with ternary feldspars with high An contents (approximately An_{50}). Under P_{H_2O} conditions, leucites may only coexist with alkali feldspars even poorer in Ab than those found at atmospheric pressure. Rare occurrences of coexisting leucite and Na-Feldspar in nature have probably not crystallized directly from a melt, but may have formed by a process of alkali ion exchange: or they may be unstable assemblages. No support can be found for the suggestions based on thermochemical calculations that albite and leucite are compatible at high temperature.

Production of alkali-rich silica-poor liquid by melting of mantle material at greater depth

H Kuno showed that if a cross-section across the Japanese island of Honshu is taken along SE-NW direction, then it is observed that the volcanoes in the south-east are relatively SiO_2-rich alkali-poor, but as one moves north-west, the lavas become more enriched in $Na_2O + K_2O$ and poorer in SiO_2. In case of Utsuryo Island in Korea Sea, i.e. N-W of Honshu, highly ultrapotassic lavas are found. In Manchuria China, i.e. farther north-west of Utsuryo Islands, the lavas are even more SiO_2-poor, and alkali rich (K_2O/Na_2O ratio being very high).

Gupta took a simple "basalt" system, forsterite-nepheline-SiO_2. He showed that the eutectic point (where nepheline, jadeite (a pyroxene) and forsteritic olivine coexist in equilibrium with liquid) systematically shifts toward the $NaAlSiO_4$ (Nepheline) apex and away from silica as the pressure increases. If water is added, it has the opposite effect. When CO_2 is added, shift in the position of the eutectic is similar to dry pressure.

Eutectic composition refers to the composition, which corresponds to the composition of the first liquid. This was experimental demonstration of the fact that with increase of pressure or depth, the liquid produced by partial melting of the ultramafic mantle should be increasingly SiO_2-poor and alkali-rich. He experimentally arrived at the same conclusion, when he studied the system $KAlSiO_4$-Mg_2SiO_4-SiO_2 with or without volatiles (H_2O or CO_2).

Fabrication of high pressure-high temperature laboratory

Gupta has constructed a high pressure- temperature laboratory at the University of Allahabad during last five years. The high pressure equipments fabricated here are capable of maintaining pressure and temperature up to 50 kbar and 2000°C, respectively. At this laboratory, processes occurring at the upper part of the mantle can be simulated. The laboratory is well-suited for experiments, which can be run for more than a week; the introduction of such high pressure equipments and facilities in the field of Earth sciences in India, has revolutionized the methods of petrological studies in India. He has done pioneering work in the field of experimental petrology.

Morograph or the genesis of leucite-bearing volcanic rocks

Gupta completed 20 pseudo ternary and several pseudobinary systems in relation to the genesis of highly potassic mafic and ultramafic rocks, the results of which are summarized in a book in the form of a monograph, published by Springer Verlag, Germany. This is a standard reference book on leucite-bearing rocks.

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Dharmajit Guptasarma

Guptasarma has contributed mainly in the field of exploration geophysics. He has carried out theoretical and experimental work to elucidate the phenomena of induced polarisation and electromagnetic induction as applied to geophysical exploration. He designed numerical filter operators for fast, computer based interpretation of exploration geophysical data. In the area of instrumentation, his most important contributions are in the design and development of airborne and ground based electrical, electromagnetic and magnetic prospecting apparatus of different types, and laboratory scale modelling of EM and IP responses of idealised targets.

Electrical and electromagnetic (EM) induction prospecting : Guptasarma was the first in India to design and construct a full-scale electromagnetic induction prospecting apparatus to make measurements of the complex transfer function between the source and the detector at one or more frequencies, for locating subsurface geologic conductors[1].

Guptasarma was the first to point out the essential difference between the phenomena of purely inductive interaction between a target and its surroundings, and conductive interaction between them[2]. This study has been described as one providing current understanding of the electromagnetic response of complex three-dimensional geologic models.

By building an operating airborne pulsed transient EM prospecting system to confirm his theoretical studies, he has demonstrated that a good deal of geological noise produced by near surface, poorly conductive overburden material can be eliminated, if the transient induced field, rather than its time derivative, is measured[3]. Earlier to his demonstration of this principle, the measurement of the transient field was thought to require faster magnetometers yet to be invented. He avoided this difficulty by fast sampling of the time integral of the voltage induced

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in a pick-up coil used as the sensor. His innovative development work in airborne geophysics for the exploration of minerals has resulted in the establishment of indigenous capability in this area.

In ground exploration with repetitive pulsed electromagnetic excitation, Guptasarma has demonstrated that measurements can be made over the entire transient signal cycle, if a controlled source is used. Using this principle, he built a microprocessor-based system that effectively makes measurements over a wide bandwidth. In this system he has also demonstrated a novel approach to reduction of impulsive noise caused by thunderstorm activity.

Guptasarma has provided a simple proof of the fact that the response of a coincident loop transient EM prospecting system cannot change its sign during the transient decay, except in the presence of frequency dependent conductivity, or permittivity[4]. At that time transient EM responses with changing polarity were being variously interpreted wrongly in terms of underground conductivity distributions. The importance of the result is the understanding that a change of sign of the transient signal signifies the presence of electrochemically polarisable material in the ground, such as disseminated sulphide ores. This indicates the possibility of detecting buried polarisable material by inductive EM prospecting tools.

In the geophysical literature there was a so called theorem for direct current regimes which was essentially erroneous in its concept. Guptasarma demonstrated that this theorem was wrong[5,6].

Induced polarisation (IP) : Electrochemically polarisable material, such as metallic ores of copper and lead, graphite and magnetite, show a frequency dependence of their resistivity at low audio frequencies. The actual spectrum of the magnitude and phase of the resistivity depends on the material and, different polarisable minerals could have distinguishably different complex resistivity spectra. The spectrum of resistivity measured over a buried polarisable target, however, differs from the true spectrum of the target. The relationship between the observed and the true polarisability spectra has been investigated into for over 30 years by many workers. It had been observed that many real targets have a minimum-phase-shift type polarisability spectrum. Guptasarma has shown analytically that in such cases the true and the apparent spectra can be related through a simple approximation[7]. This finding has the potential of being used for discriminating between one type of buried polarisable material and another, for which no other method exists. This could, under suitable field conditions, make it

possible to determine from surface measurements whether a particular IP response is due to a sulphide, or graphite or magnetite, for example.

There was a long standing practice of physical scale modelling of apparent electrical resistivity by using electronic conductors, such as metal sheets and cylinders, to represent conducting targets, by suspending them in an electrolytic tank. The results of such modelling were used to prepare master curves for the interpretation of electrical resistivity measurements for the exploration of minerals. Such modelling was being done in many laboratories around the world, ignoring possible errors caused by electrochemical polarisation at the interface between the model target, and the electrolyte. Through a set of carefully controlled experiments, Guptasarma[8] has shown that the errors may indeed be extremely large, even to the extent of making an electrically conducting target appear to be an insulator. The mechanism of such errors, brought out by Guptasarma, has also been checked out by numerical modelling by other workers abroad. Guptasarma's study of this effect has changed the approach to electrolytic tank modelling all over the world.

Digital linear filter operators : Digital linear filters have been in use for over a decade in numerically evaluating certain infinite integrals, which appear in the calculation of the electrical and EM response of the ground. Such operators are used, instead of carrying out Gaussian quadrature, in integrating functions which are characterized by slow, oscillating decay. The accuracy that can be attained by carrying out Gaussian quadrature depends on the number of terms used and, as a consequence, attainment of higher accuracy requiring a correspondingly larger computation effort. With the digital filters which are used for particular applications in exploration, reasonable accuracies were attained by using not too large operators. Guptasarma has devised a method of optimising the design of such operators[9] in a manner that the error, for comparable number of elements in the operator, is reduced by a factor which can be as large as 1,000. Such operators may be designed to achieve higher accuracy of results for comparable computation efforts, or much faster computation for comparable accuracy, or something of both. The method is very general, and can be used for a large variety of linear transformations, if the transformation can be done in closed form in any one case.

One such linear filter operator designed by Guptasarma is specifically for use in the computation of the transient response of an electrochemically polarisable ground under electrical excitation[10]. The formal integral required to be evaluated in this case is the inverse Laplace transform of a frequency function

containing varying fractional powers of the complex frequency variable. Since closed form integration of such expressions is not possible, the practice was to use different approximations for early and late values of the response, each of which is in error in some critical range of time. The digital filter operator designed by Guptasarma for carrying out the same computation, which only requires the evaluation of the sum of a number of products, eliminates all such difficulties in one stroke.

Magnetometry and other instrumentation related to geophysical exploration : Proton precession magnetometers are widely used in geophysical exploration for surface, air or shipborne measurements. To start free precession of protons in the sensor sample, a strong polarising magnetic field set up over the sample is suddenly withdrawn in a very short time. Normally no precession can be detected if the withdrawal takes longer than half the precession period. This makes it necessary that the sensor be kept away even from non-magnetic metallic objects such as metal sheets, and makes it impossible to shield the sensor in locations where external electrical noise may be too large.

Guptasarma was the first in the country to make portable proton precession magnetometers. Guptasarma has devised a method of signal generation that does not require fast withdrawal of the polarising field at any stage. In addition to making it possible to use screens for the sensor, this method avoids the need for using a mechanical switch. Proton precession magnetometers using this principle are being commercially manufactured in the country.

Guptasarma has made many other instruments for application in exploration. Apart from making an airborne optically pumped magnetometer using a rubidium vapour cell, and other ground, airborne and shipborne exploration and data acquisition apparatus, he has also made devices such as a portable magnetic susceptibility meter for measurements on rocks *in situ*[11].

Distributed amplifiers : Very early in his career Guptasarma devised a method of improving the frequency bandwidth in distributed amplifiers using vacuum tubes[12].

Diamond exploration : Diamonds have been known in India before they were known elsewhere. The best diamonds found so far anywhere in the world have not yet excelled in quality the famous diamonds of south India, such as the Kohinoor, or the Pitt. However, the source kimberlites from which these diamonds would have come have not been positively identified. It is believed that there may be some yet undiscovered kimberlites which could be the source for

such excellent diamonds. Guptasarma led a project team devoted to the study of the Cuddapah Basin in Andhra Pradesh, and the adjacent areas, in search of a method for locating kimberlites. A discovery of a new kimberlite was made near the village of Venkatampally, District Anantapur, by using the method of stream sediment sampling for indicator minerals[13]. This shows that, contrary to what was earlier believed, the method of stream sediment sampling could lead to the discovery of more kimberlites in the area. The kimberlite in Venkatampally turned out to be the most diamondiferous among all the known kimberlites in India so far, and is soon going to be exploited for commercial production of diamonds.

Geodynamics and motion of continental plates : By studying the existing global data on seafloor spreading, which is used to model the relative rates of motion of the tectonic plates of the world, Guptasarma and his colleagues demonstrated that there is a need to fill a large gap in data that exists in the region of the Indo-Australian tectonic plate, and that the best way to do that would be to set up Very Long Baseline Interferometry (VLBI) measurements with radiotelescopes in India and elsewhere[14]. He also made a review of recent developments in VLBI in its applications to crustal movement studies[15].

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Lakshminarayanapuram Narayanan Kailasam

Kailasam, a doyen and pioneer in geophysical exploration in India, as recognized by his peers, joined as the first physicist in the Geophysics Division of the Geological Survey of India early in 1946, on its inception as the first Geophysical Exploration Unit in the country. Over a period of 33 years in the Geophysics Division of the GSI, his activities in the field of geophysical exploration and research covered the entire spectrum of geological mapping using geophysical techniques; civil engineering projects; groundwater exploration, both regional and local; mineral exploration for metallic and nonmetallic minerals, petroleum and ore bodies and extensive research studies in geodynamics involving the Indian lithosphere, to all of which he has made outstanding contributions.

In the earliest part of his geophysical career in the GSI, Kailasam's work included investigation of civil engineering projects, notably the Maithon dam site of the Damodar Valley Project in 1946, involving studies of bed rock and foundation conditions, of depth, structure and topography of bedrock at the dam site and subsequently similar investigations for a major bridge site across the Brahmaputra river at Joghighopa in Assam, employing electrical and seismic techniques. These studies were followed by the investigation of the Kamptee coal field[1] in the Central Provinces near Nagpur, successfully delineating the boundaries of the hidden coal field, and the structural features of the sedimentary basin including the identification of buried faults which govern the disposition of the coal seams as well as identification and delineation of the major coal seams by virtue of their higher resistivity values relative to the enclosing sandstones and shales.

Major subsequent ground water studies conducted by Kailasam include the regional investigations of the Narmada valley in Madhya Pradesh and the Purna valley in Maharashtra[2]. The investigations of the large Narmada valley over its

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entire length and breadth proved highly successful in bringing out the bedrock depths under varying thickness of the alluvial cover of the order of 100 ft to more than 1000 ft. The lithological nature of the various buried rock formations was also identified by the contrast in their seismic velocity and electrical resistivity parameters. In the major Purna valley of Maharashtra, the electrical resistivity studies enabled the delineation of the fresh water zones within the Purna alluvium in the north to the saline zones in the south over the entire valley comprising large thickness of alluvium in the faulted river basin[2]. Similarly, the brine resources off Bharatpur in Rajasthan were investigated with successful results, delineating the zones of concentrated brine useful for salt manufacture from the less saline zones.

Other mineral investigations included the magnetic investigation of the iron ore deposit of Daltongunj in Bihar, diamondiferous volcanic pipes in the Panna and Wajrakarur diamond belts in Madhya Pradesh and Andhra Pradesh, respectively, successfully locating new hidden diamondiferous volcanic pipes. These investigations, it may be stated, were the first of their kind to be conducted in India, after the introduction of geophysical techniques for geological exploration in the country in the GSI in 1946.

At the St Louis University in the USA, Kailasam conducted field research for the investigation of the geologic structure in the flood plains of the Missouri river in the neighbourhood of St Charles, Missouri and the seismic and electrical anisotropy characteristics of the St Louis limestones under the direction of the late James B Macelwane, the renowned American seismologist and geophysicist.

In the field of oil exploration, Kailasam has made outstanding contributions in the Cambay basin[3,4] in Gujarat and the coastal sedimentary belt of Tamil Nadu. In the Cambay basin, which had been ignored by the geologists and oil companies as holding little and insignificant promise and potentialities for oil on the assumption of a shallow basin of doubtful marine rocks under the alluvium, Kailasam conducted the first reflection seismic investigations identifying a large thickness of alluvium and marine sediments of more than 2300 m within the basin, outlining the broad structure of the basin, and located and delineated the first major structure in this basin at Lunej near Cambay which was subsequently drilled by the ONGC providing oil, opening up a new, major productive oilfield in that part of the country, extending well into the Gulf of Cambay and the offshore areas of the Bombay coast, including the now well-known oil-producing 'Bombay High' and eastern coastal area of the Gulf of Cambay. Similarly, he conducted regional gravity, magnetic and reflection seismic investigations for the first time in the Cauvery basin of Madras Coast[4-6], which had also been till that

time assigned a low priority by the petroleum geologists on the assumption of a shallow sedimentary thickness. The investigation of this basin by Kailasam yielded outstanding results by the location of prominent basement structures and faults at a maximum thickness of marine sediments under the alluvium of more than 3,300 m in the deeper sections. Some of these structural features as in the Karaikal region of the coast extended well into the offshore region. Subsequent exploration activities of the ONGC in this region have proved oil over a number of these structures.

Kailasam also conducted extensive and intensive regional and geophysical studies in the field of geodynamics research, making outstanding contributions in the field under various international projects sponsored by ICSU and its affiliated associations such as the International Upper Mantle Project (1964-73), followed by the International Geodynamics Project (1973-80) and the subsequent International Lithospheric Project. His work under these projects included the study of the earth's interior in the Indian lithosphere. Special mention may be made of his regional research studies[7], again for the first time in the country, of the vast Deccan Trap region of Maharashtra, Madhya Pradesh, Mysore and Andhra Pradesh, covering an area of more than 400,000 sq km employing gravity, magnetic and seismic techniques. These studies enabled the determination of the total thickness of trap flows at several points in the vast Deccan Trap territory[8], its geotectonics and subsurface structures as also the identification of the possible lithology of the rock formations under the trap. The Koyna earthquake region was also investigated in detail[8], resulting in the identification of a major fault zone within the traps from a distance to the north of Koyna on its western flank related to Panvel flexure, extending all the way to Ratnagiri in the south on the Bombay coast, with a tectonic sag in the Koyna region. The gravity studies brought out a number of gravity 'highs' and 'lows', suggestive of market zones of uplift and subsidence involving the crust. The episodic movements of the crustal blocks as indicated by extensive epeirogenic movement in the Deccan Plateau region are reflected in the observed vertical movements[9,10].

Kailasam's other important geodynamic studies under the various international geodynamic projects are the geophysical studies of the major sedimentary basins of the Indian craton[11], their deep structural features, tectonics and their geodynamic evolution, as also the subsidence characteristics of the sedimentary basins on the continental margin of the eastern coast of the Indian peninsula[12]. He has also studied Plateau Uplift in the Indian Peninsular shield[10] with outstanding results in the Deccan, Karnataka and Shillong plateaus. He has

also made qualitative and quantitative studies of recent vertical movements in several parts of the country[13].

During his tenure as Chief Geophysicist and head of the Geophysics Department of the GSI from 1957 to 1979, Kailasam developed the Geophysics Division of the GSI as a large and well-organized geophysical exploration and research unit, both for field exploration by 50 to 60 geophysical crews annually by 1979 and a large R & D unit to support the exploration activities. The field exploration activities under his direction and guidance included investigations for metallic and non-metallic minerals, ground water and pertroleumferous structures and civil engineering projects, etc., and several experimental research studies in the R & D labs of the Geophysics Division for the study of electrical, magnetic, seismic and thermal properties of Indian rock formations and instrumentation projects leading to the design and fabrication of various geophysical instruments, viz. electrical, electromagnetic, induced polarization prospecting instruments, nuclear magnetometers, etc. Under his guidance and direction as Chief Geophysicist, more than 500 field investigations were conducted which included exploration for nonferrous metals in the major base metal areas of the country[1,14], including the Singhbhum copper belt in Bihar, the Khetri copper belt in Rajasthan, the Agnigundala copper belt of Andhra Pradesh and the Chitradurga copper belt of Karnataka, as also other nonferrous metal areas of Sargipalli in Madhya Pradesh and Orissa, Amba Mata area of Gujarat, etc. Other important investigations include the chromite deposits of Orissa, gold occurrences in the Kolar schist belt of Karnataka, the diamond occurrences of Panna diamond belt in Madhya Pradesh and Wajrakarur area of Andhra Pradesh. Ground water investigations were made in several parts of the country, in the hard rock areas of the peninsula as also the sedimentary basins[1].

During the period 1957-62, as Secretary and Executive Head of Office of the Central Board of Geophysics, Kailasam organized the Geophysics Research Wing of the GSI at Calcutta and the Oceanographic Research Wing under the CSIR at Cochin, which have been subsequently developed into the National Geophysics Research Institute and the National Oceanographic Institute by the CSIR. He also provided the nucleus of experienced geophysicists for starting other geophysical institutions such as the ONGC (1956), NGRI (1963), etc.

Kailasam has thus made notable contributions to the growth and development of geophysics research in India.

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Pancheti Koteswaram

Koteswaram began his research career in spectroscopy at the Andhra University Science College, Visakhapatnam, AP, where he worked for 3 years and obtained the D Sc Degree in Physics from the Madras University in 1939 for his thesis on the *Study of molecular association by Raman effect.*

Contribution to aeronautical meteorology

Soon after joining the Met Office, Calcutta in August, 1940, Koteswaram had to issue meteorological forecasts for aviation and cyclone warnings for the Bay of Bengal under the guidance of the senior meteorologist. In 1941 Calcutta became a base for bombing operations by the Royal Airforce (RAF) of UK against advancing forces of Japan in Burma. The IMD was expanded suddenly to meet the growing needs of the RAF and a number of new recruits were sent to Calcutta to be trained in meteorology and issue aeronautical forecast for bombing operations over occupied areas.

Severe storms of Bengal

NE India has the second largest frequency of severe storms called Nor'westers in April-May, next only to the mid-western states of USA and many of them are accompanied by tornadoes. RAF aircraft in World War II suffered occasional crashes due to these storms. IMD organised two Nor'wester expeditions in 1942 and 1944 utilising cooperating observers and sounding balloons. Koteswaram analysed surface data and identified 4 types of squall lines. The Nor'westers moved from the NW but others took different directions. He published his results in IMD Technical Note No 10, 1944, his first research paper in meteorology. In 1957, after a met radar was installed at the Calcutta Airport, Koteswaram confirmed the Nor'wester types. When he retired from service in 1975, he proposed to the GOI to setup a Severe Storms Research Laboratory (SSRL) at Calcutta similar to that at Kansas City, USA. The Dept of Science and

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Technology (DST) of the Government of India (GOI) has taken up the project recently to be started in the nineties with collaboration from IMD, University of Calcutta and the Indian Institute of Technology (IIT), Kharagpur. Koteswaram was invited to the planning conference in 1985 in which Doppler Radar Experts form NCAR, USA took an active part. Since Nor'westers are more frequent in Bangladesh than in India, the proposed laboratory has to be a joint Indo-Bangladesh project with international assistance from UNDP/WMO.

Tropical jet streams

Soon after Independence of India, National and International Civil Aviation made rapid strides over the tropics using jet aircraft. Although IMD was aware of the existence of high speed winds at high altitudes measured with the help of pibals, they did not know about the existence of jet stream. Koteswaram and collaborators analysed the R S data over India and found the existence of Westerly Polar Front (PFJ) and Sub-Tropical Jets (STJ) over northern India during the dry season (Oct-May) at about 12 km a.s.l and published the results in the *Indian Journal of Meteorology and Geophysics (IJMG)* in 1935-54. H Riehl of the University of Chicago (UCI), USA who was working on circumpolar jets over the world at that time, got interested in Koteswaram's results and invited him as a Research Associate in 1955-56. Using global data, Koteswaram identified in 1956 the existence of a Tropical Easterly Jet (TEJ) extending westwards from the East China sea to the Atlantic Ocean at about 15 km a.s.l and published his results in *Tellus,* 1958. He later found two TEJs one over the equator at about 12 km a.s.l. south of India and another over about 15°N about 15 km a.s.l. and published his findings in his lecture on Tropical Jet Streams delivered at the WMO-CAE Meeting held at London in 1969 (*JMD Tech Note*, 79).

Met facilities for International Civil Aviation

Koteswaram attended ICAO-RAN and Divisional Meetings as well as the WMO-CAE Meetings in various parts of the world from the early fifties upto 1970 and presided over many of them. He collaborated with other international experts in drawing up world-wide specifications for meteorological facilities. At the ICAO SEA/SOP Meeting at Melbourne, Australia in 1953, he proposed setting up of Institutes of Tropical Meteorology (ITM) in India and Australia for R & D in tropical jet streams. In 1958 CSM-II of WMO was held at New Delhi and recommended the establishment of a Northern Hemisphere Exchange Centre (NHEC) with HF-RTT links with Moscow, Tokyo and Melbourne for transmission of meteorological data needed by International Civil Aviation. The PR of Canada offered a HF-RTT transmitter as a gift to India and Koteswaram as

DAS established a NHEC and Northern Hemisphere Analysis Centre (NHAC) at New Delhi in 1960. In 1963 Koteswaram set up Extended Analysis and Prognostic Centers (EAPCs) at the four international airports of India to serve long haul international flights. In 1973, as DGO he upgraded the NHEC and NHAC as RTH and RTC for Asia with a DS-714 message switching computer gifted by the Govt. of Netherlands to India and an IBM 360/-44 Scientific Computer purchased by GDI. He installed self-recording meteorological instruments at the touchdown/take off areas of the main runways at the four international airports of India with telemetering arrangements to transmit the data to the ATC and Met. Units at the airports.

Tropical cyclones-disaster prevention

Koteswaram worked at the cyclone warning centres (OWC) at Calcutta, Madras and Bombay, published a paper in IJMG in 1956 on the surface characteristics of the tropical cyclones over the Bay and found that the Bay cyclones were similar to their counterparts over other tropical oceans.

Cyclone detection radars

In 1956 Koteswaram was deputed by GDI to attend the first hurricane conference convened by WMO at Santo Domingo (D R) and had the opportunity to study the latest available techniques like cyclone detection radars (CDR) and hurricane reconnaisance aircraft. On his way back home he visited the National Hurricane Research Centre (NHRC) of USA at Miami (Fla) and familiarised himself with the use of S-Band CDRs. He prepared a coastal CDR network plan for India in 1960 and in 1962 was invited by WMO as a consultant to the Regional Typhoon Conference held at Tokyo (Japan), where he delivered a course of lectures on tropical cyclones of India. He examined the typhoon warning work by JMA at Tokyo and selected an S-Band radar for the proposed CDR network in India. The radar arrived at New Delhi in 1964 and was installed on the Dolphins' Nose hill at Visakhapatnam (AP) by end 1969. A CDR network was set up along the east and west coast of India between 1970-75 with imported as well as indigenously made radars.

Meteorological satellites

At the University of Hawaii Koteswaram studied the first satellite pictures of the tropical cyclone over the Arabian Sea. He noticed an asymmetric distribution of cloud bands around the storm with almost clear sky in its central region. He published the findings in a report of the University of Hawaii in 1961 and the asymmetric banding has now become a standard pattern in Dvorak's satellite

imagery classification of cyclones drawn up after studying tropical cyclones all over the world.

As an essential requirement of the meteorological component of the International Indian Ocean Expedition (IIOE) planned by Koteswaram at the University of Hawaii in 1961 in collaboration with C S Ramage of the Department of Meteorology, the National Science Foundation (NSF) of USA gifted an APT receiving equipment to be set up at the International Meteorological Centre (IMC), Bombay in 1963. This facility has continued at Bombay till 2 years ago and has identified every tropical cyclone over the Indian seas since 1963. Koteswaram got APT sets manufactured in IMD Workshops in 1971 and installed them at the WCs and other important Met. centres in India. In 1982, The Indian Space Research Organisation (ISRO) located a geostationary Indian National Satellite (INSAT 1-B) which keeps the cyclones over the Indian seas under constant surveillance. The satellite has also been provided with facilities for disseminating automatic disaster warnings and reception of data from unmanned data communication platforms (DCPs) along the coast.

Vertical structure of tropical cyclones and disaster prevention

Koteswaram was invited by the National Hurricane Research Centre, Miami (Fla) in 1964 as a visiting professor and spent 3 years investigating the vertical structure of hurricanes. He found that the core of the tropical cyclone extends upto the tropopause and beyond with a cold top above the warm core below due to overshooting of CB clouds into the stratosphere. He published his results in the monthly weather review (MWR) of USA in 1966 and got them verified in Indian cyclones.

Research and development

Koteswaram was well aware from the fifties onwards of the importance of cyclone reconnaissance over sea by aircraft and tried to provide such a facility for the Indian cyclones from Indian resources and/or UNDP/WMO assistance. He set up a Cyclone Warning and Research Centre (CWRC) at Madras in 1974 to provide a research base for the Bay of Bengal-Arabian Sea cyclones.

WMO Tropical Cyclone Project

After a disastrous tropical cyclone hit E. Pakistan (now Bangladesh) in 1970, and killed more than 200,000 people, the Govt of Pakistan approached UN for help. The WMO Congress that met in Geneva in the spring of 1971 was requested by UN to take necessary action and selected Koteswaram as Chairman of a panel of eight International Experts to draw up a World Tropical Cyclone Project. The

panel met at Tokyo in 1972 and submitted its report to WMO in 1973 for adoption by cyclone prone countries all over the world.

Monsoon research

After identifying the TEJ in 1956, Koteswaram traced its origin to the summer heating of the elevated Tibetan Plateau. Since it was located above the summer monsoon in the lower troposphere, he postulated a meridional monsoon cell (MMC) theory in which the normal Hadley Coll is reversed as the heat source over Tibet. The TEJ forms in the upper tropospheric outflow and the monsoon westerlies as the low tropospheric return flow of the MMC. Koteswaram presented his MMC theory at the conference on monsoons of the world convened at New Delhi in 1950 and published by IMD in 1960. The validity of the theory was soon in daily satellite cloud pictures since 1960 and has been also verified by vertical wind analyses by a number of workers.

In 1967 Koteswaram was invited to NCAR, Boulder (Colo), USA as a visiting scientist and along with Van De Boogaard collected three-dimensional data during July on a world wide basis and analysed it with the CDC 7600 computer there in order to identify the role of the ASM in the global circulation in the northern summer. An atlas of mean circulation of the tropical and subtropical atmosphere in July was published by Van De Boogaard at NCAR in 1976.

Koteswaram explained the formation of monsoon depressions in 1958 as due to upper easterly waves in the tropical easterlies. Recently he analysed the development of monsoon revival depression (1987) and is at present studying the 3 D structure of the active and break phases of the Asian Summer Monsoon which are for the occurrence of recurring floods and droughts over South and East Asia. He is at present making a 3 D study of the mean Afro-Asian Summer monsoon over both hemispheres.

International Indian Ocean Expedition (1963-66)

An International Indian Ocean Expedition (IIOE) was planned by NSF of USA in 1959 and Koteswaram was deputed by IMD to collaborate in organising International Meteorological Centre (IMC) at Bombay for the IIOE in association with C S Ramago of the University of Hawaii. The IIOE which was conducted during 1963-66 under the auspices of WMO obtained financial support from the U N Special Fund to purchase an IBM 1620 computer and provide a few international meteorological experts at the IMC. The US Weather Bureau stationed four highly instrumented aircrafts of its research flight facility (RFF) at Bombay during the monsoon season of 1963 and conducted regular flights in the

Arabian Sea monsoon at different levels releasing drop sondes. The NSF gifted an APT received to IMC as mentioned earlier. The RFF visited Delhi in 1963 and gave a demonstration flight.

At the end of IIOE, IMC with its IBM 1620 computer, data and weather charts collected by Bombay were shifted to IMD Pune, where an Institute of Tropical Meteorology was organised by IMD in 1963. IIOE was thus the first major scientific expedition organised in the ASM and produced data base for a series of scientific papers and atlases produced by participating scientists from India and USA. Ramage wrote his book on *Monsoon meteorology*. Although he had planned and organised IIOE, Koteswaram did not participate in it and joined NHRL, Miami on invitation during 1964-66 as a visiting professor to study tropical cyclones and to NCAR, Boulder (Colo) in 1967. He was well aware of the need for more intensive R and D into the ASM after the IIOE and made global preparation by study of the tropical and sub-tropical atmosphere in the northern summer.

Climatological research

After returning from USA in 1960, Koteswaram worked for a year as Dy D G O Climatology at Pune in 1968-69, when he computerised the work of the climatological division there with the aid of the IBM 1620 computer at ITM and investigated trends and periodicities in monsoon rainfall over India using the long series of monthly and annual rainfall for a number of stations over periods extending to a country and more. He determined short and long term periodicities related to sunspot activity and published his results in various journals including the 75th anniversary volume of the journal *Idajoras* of the Hungarian Meteorological Society to which he was specially invited to contribute his paper. He continued his work in recent years (1985) and is in search of a relation between monsoon rainfall over India and sunspot activity.

Monsoon experiments

Koteswaram proposed as delegate of India at the WMO-ICSU meeting held at Brussels in 1970 that in order to assist the economies of about one and half of the population of the earth living in South and Southwest Asia and South China and dependent on the ASM for agriculture, irrigation, hydropower etc., a monsoon experiment (MONEX) should be integrated as a part of the GARP. The proposal was accepted and MONEX was planned to be implemented in 1979 as the GATE was planned in 1974. After a devastating drought in India in 1972, Koteswaram got into an agreement with Acad Federal of USSR to conduct joint Indo-USSR Monsoon Experiments-ISMEX 1973 with the aid of four oceanographic research

vessels supplied by USSR and two Indian Naval Ships equipped by IMD. He recommended to GOI to provide sufficient funds to conduct the International MONEX proposed by him at Brussels in 1970 and planned at Singapore in 1975. MONEX-1979 was the biggest scientific experiment carried in the ASM. Large number of meteorologists from various countries busy in their quest to understand the physics of this global phenomenon.

Reorganisation of IMD

As Koteswaram was interested in R & D as well application of the science of meteorology for the uplift of the country's economy he made a number of structural changes during his service in the IMD. The following are some of the noteworthy improvements made by him.

Instruments : IMD pioneered from even before World War II in making all the met. instruments needed in its network. It developed two types of electromechanical radiosondes (RS) which were found unsuitable after the advent of jet aviation in the fifties. Koteswaram changed over to a single audiomodulated type all over the country in the early seventies. Since these instruments did not provide accurate temperatures at high levels, he proposed to GOI that an autonomous Geophysical Instruments Manufacturing Organisation (GIMO) should be established in the Public Sector and implement strict quality control adopting modern techniques used by manufacturers in other developed countries. This scheme has not yet been implemented by GOI. He however persuaded instrument manufacturers in the country to make sophisticated instruments like meteorological radars which are replacing imported instruments. The IMD was awarded an import substitution award by the GOI during his term as DGO—the only occasion to be so recognised till now.

Telecommunications : As mentioned earlier, Koteswaram as DAS established a NHEC of the WMO at Delhi in 1960 and upgraded it to a RTH in 1973 with the aid of a DS-714 message switching computer gifted by the Govt. of Netherlands and a LUCH equipment provided by HMS of USSR. The telecommunications computer was installed in 1976 processing data at a speed of 2400 b/s on satellite channels.

Satellite meteorology : Koteswaram established a directorate of satellite meteorology in the early seventies to manufacture APT receivers for monitoring NOAA satellites and provided Radiofacsimile circuits with Moscow to receive satellite imageries from USSR Meteor Met. Satellites, IMD was thus enabled to receive satellite cloud imagery since 1963. Since 1982 ISRO provided INSAT

1-B that keeps continuous watch on tropical cyclones over the Indian Sea areas. The division of Satellite meteorology at IMD Delhi became the Met. Data Utilization Center (MDUC) and is connected by satellite channels to subsidiary data utilization centres (SDUC) at the capitals of various states in the country. It was upgraded by the GOI as the National Centre for medium range weather forecasts (NC-MRWF) set up by DST in 1989.

Hydrometeorology : In the early seventies Koteswaram set up a Directorate of Hydrology at New Delhi and a network of flood meteorological offices (FMOs) for all the flood prone rivers of India as recommended by a high level committee of Ministers of Central and State Governments and experts including himself. He provided for installation of S-Band radars to estimate rainfall in the catchment areas of the rivers but these have not been set up as yet. In 1973 he organised a UNDP/WMO project for developing flood forecasting procedure for the catchment of the River Yamuna by the Central Water Commission (CWC) and IMD of GOI. He was fourth president of the INC-IMD and contributed an article on *Climate and meteorology of humid tropical Asia* to the UNESCO Publication on Natural Resources of Humid Tropical Asia in 1974.

Agricultural meteorology : The IMD that started as a unitary department for the whole country when it was founded by the British Government in 1875 was regionalised into seven regional centres (RCs) in 1947. In the early seventies Koteswaram as DGO decentralised the IMD to the level of different States and established Meteorological Centres (MCs) at the capitals of all important States. Since service to agriculture forms the most important functions of the MCs, he initiated an Agrimet Advisory Service for the benefit of the farmers in each district as recommended by the Agrimet Committee of the National Commission on Agriculture in 1974 of which he was the Chairman. These AAS bulletins are issued by the M C in the capitals of the State in consultation with experts of the local Agricultural Universities. In the absence of mathematical models for the tropics, these bulletins are issued on a subjective basis.

After a drought affected the country in 1992, the then P M appointed a committee of experts to suggest ways and means to issue medium range forecasts for 5-10 days ahead using the imagery received from INSAT-1 B and sophisticated computers. As recommended by the Committee, a National Centre for Medium Weather Forecasting (NC-MRWF) was started by DST in March 1989 and a Super Computer CRAY XMP-14 imported from USA to develop necessary forecast models as mentioned earlier. The R & D at the centre is still at

an experimental stage as India is the only country in the tropics to attempt computer modelling of weather 7-10 days in advance for 240 agro-met divisions.

Drought research : After severe droughts affected India in 1965-66, the planning commission of the GOI requested IMD to investigate droughts. Koteswaram commenced a drought research unit (DRU) at IMD, Pune in 1970 to identify suitable indicators of agriculture droughts and develop crop-yield forecast equations for major crops in different districts of the country. These statistical forecasts are supplied to the GOI every year for water and crop management.

Numerical weather prediction : Koteswaram started a national working group in NWP consisting of interested experts in 1970. The IMD developed a geostrophic model at Delhi and ITM a PE model and experimented with the computers available in the IMD and elsewhere in the country. As mentioned above, a super-computer was installed recently. India has thus emerged as a pioneer in NWP in the tropics. Although computers have been installed, Koteswaram is well aware of the serious deficiencies in observations, internal telecommunications and tropical models in India and elsewhere in the tropics. With the advent of satellite monitoring techniques on a global basis in the coming years, he hopes that forecasting Indian monsoons by NWP districtwise will become possible in the next century.

Environmental meteorology : GOI started a National Committee for Environmental Planning and Coordination (NCEPC) in 1970 with Koteswaram as one of the founder members. He was deputed in 1972 as delegate to the UN Conference on Human Environment (UNCHE) held at Stockholm, Sweden where the UN Environmental Programme (UNEP) was initiated. As DGO Koteswaram started Background Pollution Monitoring (BAPMON) Stations in India in collaboration with UNEP and WMO, established a directorate of air pollution at IMD, Pune to advise emerging industries and set up micrometeorological towers at the Visakhapatnam Steel Plant and elsewhere.

Ozone monitoring : In the early seventies Koteswaram started balloon borne ozone sonde ascents in the country in addition to the network of Dobson spectrophotometers which have been functioning for a long time.

Stratospheric and Mesospheric meteorology : In order to study the structure of the stratosphere and mesosphere, Koteswaram started a division of stratosphere and mesosphere meteorology at IMD Pune in the early seventies making use of the weekly rocketsonde ascents taken upto levels of about 100kms a.s.l. at the

Thumba Equatorial Rocket Launching Station (TERLS) near Trivandrum, established in 1963 by ISRO to fire the met. wind finding rockets supplied by NSF (USA) for IIOE. The rocketsonde ascents have continued with M-100 met.rockets supplied by HMS of USSR since then. Indian versions have been developed by the Indian Institute of Tropical Meteorology (IITM) to be fired by Rohini rockets of ISRO after the Russian supply is discontinued.

Weather modification : In 1974 and 1980 Koteswaram was appointed Chairman of National Working Groups set up by GOI to recommend weather modification techniques for drought mitigation and hail suppression. IITM, Pune has experimented with warm cloud seeding using common salt successfully during the past 12 years and DST plans to set up the Indian Weather Modification Organisation (IWMO) in the nineties.

Formation of autonomous Research Institutes

In accordance with the recommendation of a Committee for Scientific Research (COSR) appointed under the Chairmanship of Late Prof. S Bhagavantam by late PM Jawaharlal Nehru in 1960, Koteswaram established in 1971, three divisions of the IMD as autonomous Research Institutes—the Indian Institute of Tropical Meteorology (IITM) Pune, the Indian Institute of Astrophysics (IIA), Kodaikanal at Bangalore and the Indian Institute of Geomagnetism, Bombay. The Directorate of Scientology at Delhi has not yet been constituted into an autonomous institute for various reasons. Koteswaram was the first Chairman of the Governing Council of IITM in 1971-75 and member during 1979-83. As President of the National Committee for Astronomical Research (NCAR) in 1969-71, he approved a proposal to setup a 2 meter optical telescope in South India and provided funds initially from IMO for starting the manufacture. The telescope has since been manufactured mostly by Indian scientists and installed about 2 years ago at Kavalur near Madras in memory of the Late Dr Vainu-Bappu the first Director of IIA who proposed the project.

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Anna Modayil Mani

Mani's earliest work, carried out at the Indian Institute of Science, Bangalore, was on the fluorescence, absorption and scattering of light in ruby and diamond. A detailed study of the fluorescence and absorption spectra of diamonds of widely different intensities and colours of luminescence showed the existence of a clear relationship between the two spectra, both in their general character and their intensities. The frequency differences between the principal electronic lines and the lattice lines were found to represent the vibration frequencies of the diamond lattice.

Mani's later work in the India Meteorological Department at Pune was in atmospheric physics—cloud and rain physics, atmospheric electricity, atmospheric ozone, radiation—and instrumentation. Radar studies of thunderstorms and of precipitation processes in clouds provided quantitative information on the rates of growth and dissipation of thunderclouds, the nature of the "melting band" and the initial release of precipitation in clouds.

In addition to the design and development of a number of instruments for routine meteorological measurements, instruments for measuring the various short-wave and long-wave components of the radiation balance of the earth and the atmosphere were developed during the sixties. A network of radiation stations for regular measurements of direct, global and diffuse solar radiation, long-wave and net radiation and the albedo were established and a radiation climatology for India and its neighbourhood evolved. Aircraft measurements of the upward and downward short-wave radiation fluxes and balloon measurements of the vertical distribution of the infrared radiative fluxes in the atmosphere were also carried out at the same time.

The study of the depletion of the downward beam of radiation in selected spectral bands has provided valuable information on the dust content of the

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troposphere and stratosphere and provided data on an aerosol climatology for India. Normal concepts regarding atmospheric turbidity parameters have to be radically altered to fit in with Indian observations especially during the premonsoon months.

Atmospheric ozone is a very important parameter in the study of the fundamental physical processes affecting the energetics and motions of the atmosphere. An electrochemical ozonesonde to measure the vertical distribution of ozone in the atmosphere was developed at Pune and is now flown from a number of stations in India. Ozone exists in relatively small concentrations throughout the troposphere, the concentration increasing markedly with height in the lower stratosphere, reaching a maximum at 25-28 km. Studies of latitudinal and seasonal variations of ozone have shown that information on the formation and transport of this atmospheric tracer, a quasi-conservative property below 20-25 km, is of great importance in understanding the physics and dynamics of the atmosphere.

Measurements of atmospheric electricity, the electrical field, the electrical conductivity of the air and the air-earth current, are also important, providing as they do a valuable index of the time variations of global electrical activity. Measurements of these parameters, both at the earth's surface and in the free atmosphere, using electrographs and balloon-borne electrosondes, have provided information on their seasonal variations and further evidence of the presence of dust layers in the stratosphere.

Mani's recent work at Bangalore relates to studies of solar and wind energy resources and the preparation of climatological data handbooks for India. Using both measured data and theoretical models, radiation data of importance to solar energy users have been compiled/computed and published in two volumes, for nearly 150 stations in the country, and wind data at 400 stations for the design and use of wind energy conversion systems in the third volume.

Since 1984, Mani has been involved mainly with wind energy resource assessment in the country for the identification of strong wind sites to establish wind farms for power generation, covering 15 States and 2 Union Territories. The wind mapping project for the preparation of national and regional wind atlases covers 21 States. Data collected at 50 wind monitoring stations were published in two volumes.

The recent scare of "ozone holes" in the Antarctic and Arctic, led Mani to examine the data for over 30 years, from all ozone measuring stations in the

tropics, to see if any depletion in ozone has been recorded in the tropics in the last three decades, but he found no significant trend of ozone depletion other than the normal variability in the ozone amounts.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Sukumar Shyamlal Merh

Merh has specialized in structural geology. He wrote his PhD thesis on Scottish highlands, at the Imperial College of Science & Technology, London. After his return to India in 1960, he actively worked in Kumaon and Nepal Himalaya for almost 20 years.

Merh is known for his original contributions in the field of structural and metamorphic geology and quaternary geology. He has worked extensively in the Himalayas of Kumaon and Central Nepal and is one of the noted workers in Himalayan geology. He has also contributed substantially to geological studies in the Precambrians of Gujarat.

Merh has diverse research interests, and in recent years he has been devoting attention mostly to quaternary geology. He formulated a multidisciplinary research programme on quaternary geology relevant to India. As a quaternary geologist, he has worked on the Gujarat and Saurashtra coastline, Rann of Kutch, Miliolite rocks of Saurashtra and continental sequences of Mainland Gujarat.

The Department of Geology at Baroda, which was started by Merh, has in the course of the last 30 years, developed into a reputed centre of postgraduate teaching and research in the country.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Santosh Kumar Mishra

Mishra has a strong background of dynamic meteorology, partial differential equations and numerical methods. His important contributions relate mainly to the development of simple analytical models for simulation of monsoon circulation and disturbances, development of numerical spectral models for monsoon impact studies, instability studies and energetics associated with the south-west monsoon disturbances with particular reference to: the onset of the south-west monsoon, the formation, growth and movement of monsoon depression and the disturbances along the tropical easterly jet stream of the upper troposphere. He also contributed significantly on nonlinear dynamics of monsoon disturbances.

Analytical simulation of annual march of monsoon circulation

It is well known that the seasonal variations in the solar radiation and the pronounced land-sea contrasts generate and maintain the monsoon circulation over South Asia.

A simple, linear, time dependent, quasi-geostrophic thermally forced mathematical model in the meridional plan, which also included the effect of Ekman boundary layer friction for evolution of monsoon circulation, was proposed and solved. The analytical solution of the model was able to simulate several observed features of the zonal wind pattern and their seasonal variations. Following are the important findings based on the model: (i) The effect of planetary scale forcing, which is confined close to the surface is felt even up to troposphere, while the influence of synoptic scale forcing would hardly reach the upper troposphere. (ii) The vertical velocity induced by the friction penetrates deeper into the atmosphere, provided the involved horizontal scales are large[1].

Mean monsoon flow and baroclinic instability condition

To determine mathematically whether the observed monsoon westerly and easterly jets satisfy the necessary condition for baroclinic instability condition and

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to determine the realistic thermal response during monsoon and for many other studies, the need of an analytical model for mean monsoon zonal wind and static stability was felt. Mishra developed such a model[2], which was also used to determine analytically the condition for the westerly and easterly jets to satisfy the necessary criterion for baroclinic instability[3].

Horizontal motion of monsoon depression

To provide a satisfactory explanation for the upstream propagation of monsoon depressions against the low level monsoon westerlies is an important problem of monsoon dynamics. To eliminate uncertainty associated with numerical computations, a simple analytical model was developed by Mishra to represent the 3-D structure of mean monsoon depression[4]. The model was used to study the horizontal movement of monsoon depressions analytically and on the requirement that the horizontal motion should be uniform in the vertical, he inferred the necessity of vertical transport of cyclonic vorticity from boundary layer to the upper layer ahead of monsoon depression, which was inferred by other workers based on the vorticity budget studies[5].

Genesis of monsoon depression

The depressions which form at the head of Bay of Bengal and move west-north-westwards across the central part of the country are important synoptic weather systems of the south-west monsoon. The instability of monsoon zonal flow was the subject of several studies to explain the formation of monsoon depression without success. The baroclinic instability of monsoon zonal flow has a positive role in the formation and growth of monsoon depression was shown for the first time by Mishra and associates, using a vertical high resolution linear numerical model[6].

Onset monsoon vortex

In majority of years, the onset of south-west monsoon over the Kerala coast is in association with the formation and northward movement of onset monsoon vortex over the south-east Arabian Sea. A few studies were done, using observed data collected over the Arabian Sea during MONEX 1979, to understand the formation of vortex. These studies used an atmospheric model, which has restrictive applicability close to the equatorial region. Mishra and associates using a more realistic model have shown the low-latitude Cyclo-genesis leading to the formation of onset vortex, as due to the barotropic instability process. They also pointed out that disagreement between theory and observations arises mainly from the superposition of vortex on the large scale background flow[7].

Mishra and associates were the first to study systematically and complete energetics of an observed onset vortex. They provided the following possible scenario regarding the formation and growth of the onset vortex. First Meridional and vertical shear of zonal wind are strengthened. The formation of the onset vortex occurs once the threshold values of the shears are attained[8].

Genesis of upper tropospheric disturbances

Disturbances originate in the vicinity of tropical easterly jet during summer monsoon and travel from east to west with a speed of 10-12 ms^{-1} and have a wavelength of about 5000-6000 km. Mishra and associates investigated the mechanism of their formation, growth and movement in a series of studies[9-11]. They also established important dynamical role played by the observed asymmetry of easterly jet and the spherical geometry of the earth.

Nonlinear dynamics of upper tropospheric disturbances

It was realised that the major weakness of the theories proposed for the genesis of atmospheric disturbances lies in the assumption of disturbances as a single wave mode of an infinitesimal small amplitude, thereby neglecting nonlinear interactions. Mishra studied the nonlinear evolution of perturbation superimposed on the observed easterly jet by integrating barotropic nonlinear global spectral model for 120 days. It was shown that nonlinear interactions contribute positively towards the scale selection to such an extent that finally at steady state a single wave is effectively present. It was found by him that nonlinear interactions bring the model disturbance close to the observations[12].

Numerical methods

Numerical modelling of the atmospheric circulation and processes emerged as the important tool for a better understanding of monsoon dynamics and physics. Development of numerical models is in the forefront of atmospheric studies. Mishra has specialised in the development of atmospheric spectral model. He suggested a new algorithm for efficient and accurate computation of zeros of legendre polynomials[13]. He also suggested a number of modifications in the Fast Fourier Transform (FFT) algorithm to further increase its computational efficiency[14].

Spectral models

Many operational centres around the world have developed atmospheric spectral models for operational numerical weather prediction. The spectral models are widely utilised, in addition to numerical weather prediction, for general circulation simulation and different dynamical studies of the atmosphere. The first

indigenous barotropic primitive equations spectral model was developed by Mishra. Subsequently, he developed a five level primitive equation global spectral model with appropriate physics. The computer codes have option to run as linear, quasi-linear and full nonlinear models. The models also provide options for triangular and rhomboidal truncations. The global as well as hemispheric versions of the models have been tested and used[15].

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Ramesh Chandra Misra

Misra had initially done extensive work on the Bundelkhand massif. Later on, he extended his studies to the Vindhyan syneclise and beyond into the Lesser Himalaya.

Bundelkhand massif

In the Bundelkhand massif, Misra remained primarily interested in mineral investigation[1]. At the same time he carried out geological mapping and petrological studies of the various granitic and gneissic rocks of the Bundelkhand region. His discovery of minerals pyrophyllite and diaspore[1] in Bundelkhand, formerly unknown in India, have helped in the development of refractory and ceramic industries. The only deposits were previously known from north Carolina (USA) and Japan. He has identified several types of granites and gneisses in the Bundelkhand complex. He presented a correlation of the gneissic rocks of the Peninsular shield. This had great implications on the problem of Basement complex in the Indian shield. Misra's work[2] also throws significant light on the vexed problem of the quarts reefs in the Bundelkhand complex.

Vindhyan syneclise

Misra had carried out extensive work on the rocks of the Vindhyan sequence. He had especially thrown light on the evidence of life during the Vindhyan period. His work[3] on Fermoria deserves special mention in this regard. Discovery of salt pseudomorph[4] shale in the Vindhyan formations of Maihar area, Madhya Pradesh which was formerly known from the Salt Range, Pakistan—is an important highlight of Misra's contribution to the Geology of the Vindhyachal region. He has discussed[5,6] the vexed problem of life in Vindhyans from several angles. While working in the Vindhyan terrain, he also remained interested in some other aspects of development of the region. For example, he suggested[7] for the first time, the Rihand Dam as a site for aluminium production and sites for cement

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factories in Mirzapur district, UP. He also carried out mineralogical study[8] of some glass-sand deposits of southern UP.

Lesser Himalaya

Misra initiated geological studies in the Lesser Himalaya in the late fifties. The department of Geology, Lucknow University under Misra's guidance was one of the pioneering institutions to work on Himalayan geology on a systematic basis. Misra guided several students for studies on geological mapping in the Kumaun Lesser Himalaya. All the areas covered by his group hitherto remained unexplored, as far as detailed studies pertaining to stratigraphy, structure, and correlation are concerned. He has delineated the structure of several structurally crucial areas of Lesser Himalaya[9] as well as those of Greater Himalaya. He took great interest in the study of stromatolites occurring in the carbonates belt of the Lesser Himalaya; such studies, of late, have been greatly utilised in establishing the stratigraphy of the Lesser Himalayan sedimentary belt. Geological studies of the Kumaun Himalaya, as initiated by Misra, are still being continued by his successors at the Department of Geology, Lucknow University.

In addition to the above, Misra studied several other aspects of Indian geology. He reported for the first time the occurrence of volcanic bomb in the Agglomeratic Slate of Kashmir. He studied[10] bauxite deposits of Bagru Plateau near Lohargada in Ranchi district. He has studied soil profiles at Banaras with special reference to the occurrence of concretions. His study[11] of Triassic conodonts and fish remains from Niti Pass, Kumaun HImalaya, is a significant contribution to Tethyan stratigraphy. Sedimentological/petrographic studies of Sone River sediments in Bihar[12] as well as those of the Gomti river, throw significant light on fluvial processes.

Some of the review articles that Misra wrote mainly at the later part of his career, provide great insight into the respective aspects. Some important reviews include the following—record of early life in rocks[13]; role of plants and microorganisms in the formation of rocks and mineral deposits[14], geological evolution of Uttar Pradesh[15].

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Asoke Mookherjee

Mookherjee's main fields of interests are: ore geology and geochemistry, regional and global metallogeny and mineral economics. Unravelling the complex interactions among geotectonic, temporal and geochemical parameters, which eventually determines how when, where and why mineral deposits were formed, has been the central theme of his research over the last four decades.

Research work on Zawar constitutes the earliest attempt[1] in this country to reconstruct the physico-chemical environment of mineralization quantitatively in terms of P, T, a_{S2} and other intensive parameters. It was demonstrated that, contrary to the prevailing notion, metal-zoning in the ore bodies is not a simple function of temperature alone. Another intriguing live problem during the fifties was: how does any ore-forming fluid perform the seemingly impossible task of holding both metal ions and sulphide ions together, avoiding precipitation? Complexing of metal ions was just being considered as a possible answer; a vital clue was furnished by demonstrating through radioactive tracer technique that partitioning of Cd, between a solution and crystals of sphalerite (ZnS) precipitating from the solution, is markedly changed when the solution is chloride-free and chloride-rich, implying thereby a significant difference in stabilities of zinc and cadmium complexes. The work[2] has been widely acclaimed.

Most ore deposits in the ancient shield areas (like those in the Indian, Canadian and Scandinavian shields) have a long, billion-year post depositional history. Post-ore geologic events like deformations, metamorphism and igneous activities had left their marks on such deposits, often to blur their pristine characteristics almost beyond recognition. Surprisingly, recognition of the imprints of the later events on ore deposits—unlike the case of metamorphism and deformation of common rocks—had been slow. The reason was partly

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historical—earth scientists having been swayed by the Lindgrenian conceptual model that most ore deposits are epigenetic and young—and partly phenomenological—the ore minerals in general being unquenchable, that is, they do not freeze the postdepositional thermal and tectonic events as effectively as the common rocks do. Some of the earliest works on metamorphism of sulphide ores stand to the credit of Mookherjee[3,4]. Further, regional metamorphism, in addition to transforming rocks, often generates geologic fluid on a regional scale; such fluid under special situations may become a potential mineralizer. Mookherjee's contributions on modifying, dispersive and 'creative' roles of metamorphism in ore generation prompted the contribution *Ores and metamorphism* in Ref. 4.

The earliest attempt in this country, in applying trace element geochemistry to solve problems of ore genesis[5], has been continued with increasing sophistication of analytical and theoretical approach[6]. Trace element signatures in ores have been used to infer the origin[5,6] and source, to deduce the temperature of formation of mineral deposits[7], and to monitor the progressive change in ore-fluid composition reflected in compositional variation of a 'sensor' mineral (tetrahedrite)[8].

Ore materials, the minerals and their fluid inclusions, constitute frozen record of natural processes and their ambient environment; very detailed investigation and thorough characterization of the materials are needed to retrieve the information[9]. Investigations carried out by Mookherjee and his Indian and Russian colleagues on the Rajpura-Dariba polymetallic deposit revealed an unusual case of superposed mineralization. They have described several very rare and one new mineral (Rayite, named after Santosh Ray, a doyen among Indian geoscience teachers) from the ore body. The series of papers[10] are widely acclaimed. Interpretation of ore textures through chemical mass balance and equilibrium considerations is a refreshingly original approach used by Mookherjee[10,11].

Current research interest extends along two directions: characterization—through thermodynamic and analytical formulation approach—of the progressively changing physicochemical variables that influence hydrothermal mineralizing systems[8,12]; and recognition of possible changes in *composition* and *style* of mineralization through space and (geologic) time [13,14]. Inasmuch as formation of ore, deposits constitutes an integral component of the evolutionary history of the crust as a whole, a parallelism in the evolutionary trends does exist. Such pattern recognition would be of great help in locating ore deposits in virgin areas.

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Dhrubajyoti Mukhopadhyay

The research activities of Mukhopadhyay cover the fields of structural geology and precambrian geology. He has worked on mechanics of fold formation, geometry of superposed deformation, finite strain measurement and structural and stratigraphical relations in the precambrian terranes of Singhbhum, Karnataka and Rajasthan.

From a detailed study of the fold shapes in the Moinian rocks of North-west Highlands, Scotland Mukhopadhyay showed that folds having similar geometry are formed by buckling followed by flattening and not by heterogeneous simple shear. This idea on the origin of similar folds has been corroborated by a number of later workers in this field. He interpreted that the divergent and convergent patterns of schistosity in the convex and concave sides respectively, of buckled competent bands result from contact strain and correlated the patterns in natural folds with experimental data.

Mukhopadhyay put forward a modified interpretation of the origin of eyed folds, a common interference pattern in superposed folding. He showed that the eyed folds in a part of the Aravalli belt in south Rajasthan resulted from strong flattening of folds with initially non-rectilinear hinge lines. He thus anticipated the currently popular model of the development of sheath folds. He made a systematic analysis of the patterns of deformed lineation in superposed folding and proposed that they can be classified into three basic patterns based on the angular relation between the early lineation and the late fold axis. He demonstrated how all of these could form by a combination of buckling and flattening. The unusual chevron pattern of deformed lineation was hitherto explained by a model of shear folding. He elucidated the special geometrical conditions in which such a pattern could form by a combination of buckling and flattening.

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Analysis of finite strain in deformed rocks has been Mukhopadhyay's prime interest. He demonstrated that the pebbles in a deformed conglomerate in Singhbhum were originally ellipsoidal and determined both their original shape and the tectonic strain. He employed a statistical method to analyse the shapes of deformed quartz grains in slates in the Hercynian belt in the Ardennes, Europe, and from these determined the finite strain parameters. He computed finite strain from folded veins and laminae in the slates and phyllites in the North Singhbhum fold belt and showed that the schistosity developed perpendicular to the direction of maximum finite shortening.

Mukhopadhyay's structural studies in the Proterozoic fold belt of North Singhbhum led to the elucidation of the geometry of large scale interference patterns produced by superposed folding. He showed that the earliest folds in the eastern segment of the fold belt are steep plunging reclined folds, on which are superposed second generation upright folds with variable plunge and curved axial planes. The regional schistosity is axial planar to the second generation folds and the main metamorphism of Barrovian type was syn- to post-tectonic with respect to this episode to deformation. On these grounds he correlated them with the folds with variable plunge and curved axial traces in the Ghatshila-Galudih region. In the western segment of the fold belt near Chakradharpur, Mukhopadhyay and his co-workers demonstrated that the regional folds are a set of northward plunging reclined folds with axial plane schistosity. The presence of very large scale eyed folds with steep northward plunging hinge lines at the two ends of the eye was also suggested. The possible presence of an earlier deformation episode was inferred on the basis of a rarely preserved older planar fabric.

The Singhbhum shear zone developed near the southern boundary of the North Singhbhum fold belt was interpreted by Mukhopadhyay as a zone of high ductile strain. It is marked by a belt of mylonites and phyllonites in the eastern and south-eastern segment of the fold belt. Along the strike continuation, the mylonite belt dies out to the west, though here mylonites are present further north within the fold belt. Mukhopadhyay and his associates emphasized that there is no structural or metamorphic discontinuity across the shear zone which is parallel to the main tectonic grain of the fold belt. The shear zone developed quite early in the deformation history, though there might have been renewed movement on it at later periods. The changing pattern of structural geometry during progressive shearing movement has been analysed in detail. On the basis of structure and petrochemistry of the granite mylonites it has been proposed that they represent

an early stage acid magmatism, probably in a rift environment related to the basin formation.

Mukhopadhyay initiated modern style structural mapping in the Dharwar craton of Karnataka and established the presence of repeated folding in the Dharwar supracrustal rocks. The geometry of superposed deformation in the Chitradurga schist belt has been analysed in detail by Mukhopadhyay and his coworkers. They showed that the overall outcrop pattern is controlled by the second phase folds and the NNW-SSE trend of the schist belt is parallel to the axial trace of second phase folds. The axial trace of a major second phase antiformal fold showing strong plunge variation passes through the central part of the belt. Near Chitradurga the fold axis is nearly vertical. South of this near Sirankatte the fold axis is gently plunging, but with a culmination, the basement gneiss being exposed in the core of the culmination. Still further to the south near Dodguni the antiform has gentle northward plunge. The hinge of a major first phase synclinal fold is exposed on the western limb of the antiform near Dodguni. Mukhopadhyay and his co-workers presented a tectonic model of the Chitradurga schist belt, in which the axial trace of the early syncline is repeated on either side of the central second generation antiform as a result of refolding. The stratigraphic sequence within the Chitradurga belt is erected on the basis of this tectonic model.

The structural investigations in the Sandur schist belt in the Dharwar craton led to a revision of the existing idea of the synclinal nature of the belt. The banded iron formations present on the two flanks of the belt are not repetitions caused by a major synclinorium, but represents different stratigraphic horizons. Asymmetrical folds formed under the influence of simple shear are superposed on first phase isoclinal folds. The structural pattern suggests its evolution under a transpressive regime.

Mukhopadhyay has worked on the geometry of structures produced by superposed deformation within the Aravalli Supergroup of Rajasthan. Large scale 'eyed folds' within the Aravalli marbles of south-eastern Rajasthan have steep plunging reclined geometry. These are first phase structures and are produced by strong flattening of folds having initially non-rectilinear axes. In an area north of Udaipur, first phase reclined folds within the Aravallis are refolded by upright later folds with N-S axial planes. The superposition has given rise to a variety of patterns of deformed lineation whose geometry is controlled by the amount of flattening relative to buckle shortening in the later folds and by the initial angle between the early lineation and the late fold axis.

Mukhopadhyay and his associates studied the polyphase deformation structures in the Delhi fold belt of central Rajasthan. The fold belt is subdivided into two segments by a thrust slice of basement gneisses. In the eastern segment the regional structural pattern is controlled by gently plunging coaxial first and second phase folds. Structures belonging to two later generations are sporadically developed. A major shear zone marking the eastern boundary of the Delhi fold belt has truncated the second generation structures Record of an earlier episode of deformation is preserved within the western segment of the fold belt and the first phase structures of the eastern segment are correlatable with the second phase structures of the western segment.

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Kshitindramohan Naha

Naha has carried out research work in three broad fields of geology : (1) structural geology; (2) metamorphism in relation to stratigraphy and structure; and (3) different aspects of Precambrian geology.

Structural geology

(i) From structural, petrographic and petrofabric studies it was demonstrated that deformation lamellae in quartz develop at a late stage of deformation, parallel to the conjugate planes of maximum shearing strain. This was confirmed subsequently through experimental deformation studies by Griggs and his associates in UCLA, USA. (ii) The properties of reclined folds and the methods of identifying them were elucidated from studies in east Singhbhum. During the last three decades these folds have been found to be common in many orogenic belts. (iii) Methods of recognizing overthrusts in metamorphic terranes involved in polymetamorphism and multiple deformation have been worked out during studies in the Simla Himalayas. (iv) Methods of elucidating large-scale architecture of migmatites, by tracing relict metasedimentary bands in folded attitudes and by analyzing them in association with minor deformational structures, have been developed. These methods have been successfully utilized in tracing the detailed history of superposed deformation in the Banded Gneissic Complex of Rajasthan and in the Peninsular Gneiss of Karnataka. (v) Methods of identifying angular unconformity in metamorphic terranes, with groups of rocks on either side of the unconformity involved in superposed folding, have been developed. These methods were used in delineating the angular unconformity between the Precambrian Aravalli and Delhi Groups in Rajasthan. (vi) A critical analysis of the concept of "orogenic trend" and its importance in the correlation of the metamorphosed Precambrian rocks of Peninsular India has shown that this concept needs significant revision. (vii) The principles of the geometry and

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mechanics of superposed folding have been fruitfully applied to unravel the structural history of the Precambrian rocks of Rajasthan and Karnataka, and the Jutogh-Chail rocks of the Simla Himalayas. Methods of recognized coaxial folding prior to non-coaxial deformation have been developed, and the nature of variation due to superposition of upright folding of varying intensity on isoclinal folds of diverse orientation has been clarified.

Metamorphism in relation to stratigraphy and structure

The variation in regional metamorphism with stratigraphic sequences and fold geometry in space, and with movement phases in time, has been studied in the Precambrian terrane of east Singhbhum and in the Simla Himalayas. (i) Structural data from the scale of map to hand specimen, and metamorphic textures in thin section have been brought to bear on the question of time-and-space relationship of progressive regional metamorphism in Singhbhum, Bihar. It has been shown that in the Ghatsila area in Singhbhum, the progressive regional metamorphism is broadly coeval with the folding movement, with the isograd surfaces accordant with the fold geometry. It has been established that the progressive metamorphic series is progressive, not only in space but also in time. The progressive metamorphic suite was affected by dislocating metamorphism along a shear zone, resulting in retrogression. (ii) Interrelation of metamorphism and deformation has also been traced in the metamorphic terrane of the Simla Himalayas (see later).

Precambrian geology

(i) Studies on stratigraphy, sedimentation, structure and metamorphism of the Precambrian rocks of the Ghatsila area in eastern Singhbhum have led to an integrated geological history of this metamorphic belt. A geosynclinal trough, bordered to the south by a granitic cratonic mass and to the north by a volcanic arc, was formed at the first stage. A thick suite of flysch sediments, derived mainly from the south, was deposited in this subsiding trough. These sediments, together with metavolcanic rocks, were involved in buckle folding with subvertical axial planes and with gentle plunge toward ESE or WNW in the first stage of deformation. Locally, the axial planes were coaxially folded into reclined folds. Progressive regional metamorphism from chlorite to kyanite grade affected the rocks contemporaneously with folding, with the higher and lower grade rocks occurring in deeper and shallower tectonic and stratigraphic levels, respectively. A dislocation metamorphism was superimposed on this progressive metamorphic

suite, owing to large-scale thrusting in the southern part of the area. Linear structures of diverse type and orientation were formed in different stages of folding, unrestricted transport during thrusting and impeded transport in the final phase of thrusting.

(ii) Work on the metamorphosed Precambrian rocks of Rajasthan has led to a revision of the stratigraphy and structure of the Aravalli-Raialo rocks and the Banded Gneissic Complex, and interrelation with the rocks of the Delhi Group. Folds of four generations have been deciphered in the Banded Gneissic Complex and the Aravalli-Raialo rocks. The latter forms a conformable sequence older than some of the supposedly basement gneisses, the gneisses representing the migmatized portions of the metasedimentary group. Evidence of granitic and gneissic rocks of more than one generation in the Early Precambrian of central Rajasthan, with mobilization of the basement during the first deformation in the Aravalli rocks, has been adduced. Criteria have been established to prove the presence of an angular unconformity between the Aravalli Group and the Delhi Group, both involved in superposed deformation.

(iii) Studies in the Dharwar tectonic province in Karnataka have shown a structural unity among all the rock groups—the Peninsular Gneiss, the metasedimentary and meta-igneous rocks forming the Dharwar Group, and the acid and basic granulites. Isoclinal folds have been involved in near-coaxial folding, followed in turn by non-coaxial upright folding, with axial planes striking between NNW and NNE. These structures, ranging in scale from cm to km, have been preceded by at least one deformation, decipherable only in small enclaves within the Peninsular gneiss. Large-scale remobilization of the basement gneiss has been demonstrated. Evidence has been adduced to show that charnockites were formed in at least two stages. A tectonic model of evolution of the Dharwar craton has been suggested.

(iv) Structural, stratigraphic and metamorphic studies in the Simla Himalayas have established that the metamorphic rocks of the Jutogh Series, structurally overlying the less metamorphosed Chail rocks along a thrust contact, have been involved in the three episodes of deformation, interspersed with metamorphism of two phases. The very

low grade rocks of the Chail Series surrounding the rocks of the Jutogh Series show a partly independent trend of metamorphism and deformation.

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Sayed Mahmood Naqvi

Naqvi has been working on Precambrian rocks of India (Dharwar Craton) since 1965. During this period, he has made an outstanding contribution in the field of Precambrian geology and geochemistry, particularly regarding the early stages of evolution of lithosphere, atmosphere and biosphere. He has also contributed towards the development and exploration of base metal deposits in Karnataka. His work has been recognized internationally and referred to and cited widely. He has established a highly sophisticated geochemical laboratory at the National Geophysical Research Institute (NGRI), Hyderabad, which is created as a national facility.

Naqvi has provided field and laboratory evidence for the existence of a primordial simatic crust made up mostly of basic-ultrabasic lavas, and its subsequent transformation to present-day sial during early Archaean to middle Proterozoic through a combination of processes mainly resulting due to interaction of the lithosphere and the hydrosphere. Along with his other colleagues of the geochemistry group at NGRI, he has shown that these processes of crustal evolution have been unidirectional and the events that occurred in the early Precambrian have not been repeated in space and time. This major and significant conclusion was drawn on the basis of the following observations.

Macro and micro spinifex textures have been recognized in the ultramafic rocks at various places in the early greenstone belts. Similarly, evidences have been obtained for the possibility of formation of the anorthositic lavas. These highly calcic anorthosites from Holenarsipur greenstone belt are comparable with lunar anorthosites. This high Ca-Mg volcanic activity of basic-ultrabasic lavas is not found in the younger sequence of the craton.

Naqvi also noticed secular variation in the distribution of elements during 4.0-2.1 Ga era and proposed 2.1 Ga as the major discontinuity in the early history

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of the evolution of the earth. Lithostratigraphic division of the Dharwar Supracrustals and Peninsular gneisses into five successive polymetamorphic interfingering groups has also been suggested by him.

Naqvi has demonstrated that the early Archaean sediments are mainly chemogenic and have unusual abundances of Ni, Cr, Mg, Fe, Al and REE patterns, indicating that the aftereffects of extra terrestrial bombardment of the earth analogous to moon during its early history have swept into the early Archaean sedimentary basins. The negative and positive anomalies found in the Precambrian sediments are independent of time-space control. His studies on the pebbles of Dharwar Conglomerate indicated that the K-rich granites were seldom present in the crust before 2.6 Ga. These granites were emplaced between 2.6 and 2.0 Ga and form a garland around the Karnataka Nuclei. An intense K-metasomatic event occurring at 3.0 Ga has also been recorded by Naqvi and his coworkers.

Naqvi's structural geology work with coworkers showed that Dharwar supracrustals and Peninsular gneisses are characterized by a 3-phase deformational structural history, but deformational signatures of still older events are preserved as bent lineations in the folded pebbles of the conglomerate and a few enclaves in 3.0-3.4 Ga old gneisses. He has envisaged that the stress directions have remained E-W during a long period of early Precambrian. The Chitradurga schist belt has originated by such E-W compression and movement. He has proposed that this belt may be an Archaean Suture. He has also recognized four different types of greywackes in the Chitradurga schist belt from N-S; their geochemistry indicates a deeper oceanic environment of formation.

Naqvi has cited numerous evidences from India to suggest that after 4.0 Ga, most of the geological processes have been controlled by hydrosphere and it is the presence of hydrosphere which has made earth unique and so different from other planets. Based on these and other studies, Naqvi, along with B P Radhakrishna, has proposed that the Precambrian crustal landmass south of Narmada-Son lineament constitutes a single landmass and has named it as Dharwar-Singhbhum protocontinent. This protocontinent constitutes three nuclei, namely Karnataka Nuclei (KN) Jeypore-Bastar Nuclei (JBN), Singhbhum Nuclei (SN) and Early Proterozoic Mobile Belt (EPMB). The nuclei and their surrounding EPMB are enclosed by the Middle Proterozoic Mobile Belt (MPMB) of Eastern Ghat and Satpura region.

Early Proterozoic Mobile Belt (EPMB) event involved sedimentation formation of amphibolite-granulite facies rocks and emplacement of K-granites in

the north and formation of charnockite and other granulite facies rocks in the south. It has been postulated that the Middle Proterozoic Mobile Belts (MPMB), namely Eastern Ghat, Satpura and Delhi belts, were produced by collision tectonics between the various protocontinental masses of Gondwanaland. Most of the Indian continental crust was formed prior to 2.6 Ga. However, it has been remobilized at least twice in the 2.6-1.5 Ga span. Karnataka, Jeypore-Bastar and Singhbhum Nuclei, characterized by BIFs and tonalitic gneisses, are the relics of the older crust, which has not been affected by later activities. Their model envisages that older schist belts were developed in shallow water basins on a simatic crust. The platformal components of the younger greenstone belts, on the other hand, were laid down in rifted basins on a sialic basement. Crustal deformation and thickening of the crust gave rise to the EPMB. At 2.0-1.5 Ga ago, another intensive mobile belt event occurred, in which subduction and flexure at the eastern and northern margins of the Dharwar Singhbhum protocontinent gave rise to Proterozoic sedimentary basins, rift valleys and igneous and metamorphic suites.

Naqvi has proposed that plate tectonic regimes had clearly set in by 2.0 Ga ago and the middle Proterozoic orogeny shows evidence of modern style collision tectonics. Subsequently, he has demonstrated that most of the characteristics of the greenstone belts are explained by his mini-plate tectonic model and shorter duration of Wilson Cycle during Archaean. His team discovered four stromatolite-bearing horizons in three localities having Archaean microbiota and established that photosynthesis and other biogeochemical processes were widespread during Archaean. These photosynthetic processes by the primitive blue-green algae provided the required oxygen to precipitate FeO as Fe_2O_3 of the BIF which are one of the prominent rock types of the greenstone belts. Along with his students, Naqvi has proposed a polygenic origin of banded iron and manganese formations.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Hari Narain

Narain started research under K S Krishnan at Allahabad University. He chose to switch over to the discipline of Geophysics and joined the University of Syndey, Australia, under a post-doctoral UNESCO fellowship. His doctoral thesis on *Regional gravity traverses in Eastern and Central Australia* is still regarded as a classic work and is often referred to in regional gravity and lithospheric studies. The estimates of crustal thickness which he made then are surprisingly close to those obtained later using more sophisticated techniques.

Narain returned to India in July 1956 and joined the newly formed Oil & Natural Gas Commission (ONGC) in Dehradun. The geophysical surveys for petroleum carried out there and a number of technical reports submitted to ONGC, merited his appointment as the first Director of the Research and Training Institute of the ONGC now known as Keshav Deva Malaviya Institute of Petroleum Exploration. His concept of integrated basin studies and search for stratigraphic traps and pinch-outs in Cambay basin proved extremely valuable in search for oil in the ONGC.

Narain joined the Council of Scientific and Industrial Research as Director of the National Geophysical Research Institute (NGRI), Hyderabad, in 1964, and has brought both national and international recognition to the Institute, over the years, through integrated studies in the various fields of Earth sciences.

Narain has been actively involved in seismological research at NGRI and has personally contributed to its present pre-eminent position in India and abroad. His work on seismic surface and body wave investigations and deep seismic sounding studies in the Himalayan-Pamir region has provided fuller understanding of, and deeper insight into, the crustal structure and tectonics of the regions[1] and of the Indian sub-continent[2].

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An estimate of crustal thickness 65.70 km in the Himalayan and Tibet Plateau region, given for the first time from studies on dispersion of Rayleigh and Love waves, was postulated by Narain and Gupta[3]. This estimate has subsequently been confirmed by many research workers.

With Gupta and Rastogi, Narain contributed significantly to the study of the Koyna earthquakes and understanding of the phenomenon of reservoir-induced seismicity[4].

A new approach for the preparation of quantitative seismicity maps, deep seismic sounding profiles along different geological units in India and detailed body wave studies have been carried out by Narain and Kaila in several regions of the world to decipher crustal and upper mantle structures[5-7].

Integrated geological, geophysical and geochemical investigations of the Indian Shield and the Cuddapah basin by Narain and his coworkers have brought to light several distinctive features of Precambrian rocks of the Indian Peninsula[8-10].

Narain's work on the Continental Margins of India highlighted some important structural features, which include the extension of the Chagos-Maldive ridge covering the Kori High and the Bombay High[11,12].

With Kaila, Narain has given a new interpretation technique of refraction data for the solution of hidden layer problems of vital importance in oil exploration[13].

Narain's active involvement in aerogeophysical surveys for the first time in the country and their interpretation has helped in delineating several distinct intracrustal structures and mineral potentialities in Karnataka, Madhya Pradesh and Uttar Pradesh.

With R K Verma, Narain has studied and reviewed the Indian terrestrial heat flow and paleomagnetic data to correlate with continental movements[14,15].

In addition to his scientific studies and researches, Narain has been strongly advocating the need for an integrated approach to scientific exploration, exploitation and management of natural resources.

As a Member of the National Committee on Science & Technology (1971-77), Narain took active part in the formulation of the Science & Technology Plan and through participation of scientists and technologists from the various institutions, such as GSI, ISM, NMDC, ONGC, CSIR, ICMR, FRI, etc., and the research institutions and universities, he brought out 12 volumes on Geodetic &

Topographic Surveys; Mineral Resources; Oil & Natural Gas; Water Resources; Forests, Land, Soil, Wild Life and Environmental Sciences.

Narain was the UNDP Chief Project Coordinator from April 1983 to December 1986, and Emeritus Scientist of CSIR up to December 1988. He has brought out a volume *Scientific research in India–Progress in earth science*, a platinum jubilee publication of Indian Science Congress Association.

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Irish Chandra Pande

Pande is one of the reputed Himalayan geoscientists. He has made valuable contribution in the various branches of the Himalayan geology since 1949, dealing mainly with evolution and origin of the Himalayan structural facies zones, illustrating marked contrast in lithostratigraphy, structure, tectonic style and metamorphic grades between them.

Origin of the structural facies belts

According to Pande's hypothesis the evolution and development of the Himalayan orogen took place in the cyclic order in response to activation of the deep seated faults (Mantle Faults) which varied in space and time as a sequel to migrating geothermal belt causing shifting of the sedimentary basins.

The Himalayan deep seated faults run parallel or subparallel to each other in a east-west direction for more than 300 km in length with a vertical displacement of 8 km. The faults from north to south namely the Karakoram, the Malari-Makalu-Sobe-Chu, the Main Central Fault (popularly called MÇT), the Kandaghat-Betalghat-Murghat Fault, the Krol/Main Boundary Fault and the Foot Hill Fault, delineate the Himalayan Orogen into east-west trending tectonostratigraphic belts.

The incoming of the Caledonian orogeny the Malari-Makalu-Sobe-Chu and Main Central Fault became energetic with the remobilisation of the foundation rock in between them. This phenomenon caused subsidence of the central faulted block between the above faults to sink into the mobile zone. This episode resulted in the origin and development of oldest geosynclinal basin. The basin was gradually filled up by Proterozoic to Early Palaeozoic sediments measuring more than 8 km in thickness. These sediments finally were lifted up as meta-sedimentaries during Early Devonian (end of the Caledonian tectogenesis). This

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positive land form has been named as the Main Central Crystalline Axial Belt (MCCAB).

The end of the Caledonian orogeny and with the incoming of the Hercynian earth movements, the geothermal belt or the Orogenic Polarity migrated to the north and to the south of the MCCAB. With this change in orogenic polarity the northern Karakoram Fault and the southern Krol/Main Boundary Fault became active and the faulted blocks to the north and south of the MCCAB started subsiding to form new amphitheatre of the geosynclinal activity.

The northern basin formed a highly fossiliferous sedimentary prism more than 6 km thick, ranging in age from the Cambrian to the Paleocene time. A marked hiatus in depositional history took place during the Permo-carboniferous time, which has been called as the Hercynian Break. The fossiliferous sedimentary prism also formed a land mass during the second tectonic phase of the Tertiary orogeny. This structural facies belt has been designated as the Trans-Himalayan Belt (THB).

To the south of the MCCAB, the sedimentary basin form synchronously with the northern basin, which has a rather more complex geosynclinal history. It forms a twin belt which is divided into an inner subzone and an outer subzone. In the early period the basin as a single unit received sediments from Cambrian to Carboniferous time. However during the Permo-carboniferous time, the Kandghat-Betalghat-Murghat Fault also became active at the end of the Hercynian tectogenesis (Hercynian Break); this episode caused upliftment of the northern inner subzone and became a landmass. The outer subzone continued to subside and receive the Permian to Cretaceous sparsely fossiliferous sediments. At the end of Cretaceous period or at the end of the Karakoram tectogenesis the outer subzone along with inner subzone and the MCCAB were uplifted. The inner subzone together with the outer subzone has been named as the lesser Himalayan Belt (LHB).

With upliftment of the LHB, the orogenic polarity migrated to the south and the faulted zone between the Krol/Main Boundary Fault and the Foot Hill gave rise to the youngest sedimentary basin. This basin received the Paleocene to Pliestocene sediments in two stages. The northern part of the basin is characterised by brakish to fresh water fossiliferous sediments, which became a landmass at the end of the Middle Miocene. The southern part of basin is characterized by fresh water fossiliferous (vertebrate) sediments. At the end of Tertiary orogeny this sedimentary belt also became a land mass and has been

called as the Tertiary Foot Hill Belt, which is separated from the Indogangetic Foredeep by the Foot Hill Fault.

Thus, according to the hypothesis of activation of deep seated fault in phased manner varying in space and time, formation of sedimentary basin, their shifting with earth's movements and uplifting metasedimentary/sedimentary prisms one after another during successive orogenies was the process or mechanism that resulted in the origin of development of polystructural orogen of the Himalaya. This theory of cyclic evolution of the Himalaya appears to be more convincing though provocative.

Structure and tectonics

Pande has made important contributions on the structure and tectonics of the different tectono-stratigraphic zones, which show a marked variation in their style, periods of their origin and geologic setting. The study includes all aspects of structural analysis and selected techniques to establish different periods of phased tectonic movements that occurred during earth movements from the Proterozoic to Holocene time. The evidences of the Vertical Tectonics for the evolution of the Himalaya are well documented in form of major, mesoscopic and microscopic structures, which when carefully analysed reveal the cyclic evolution of the structural facies belts of the Himalaya. The MCCA Belt suffered polyphased deformation during the Caledonian, the Hercynian, the Karakoram and the Tertiary orogenies. As a sequel to these phased epeirogenic upheavals, the rocks of the belt show highly contorted structures. Pande's analysis of structures reveal that these crystallines were initially folded into N-S Folds (F1) then to isoclinal folds (F2), followed by NNW trending close folds (F3) and finally ENE open folding (F4) occurred.

According to Pande's hypothesis, the central Crystallines which were repeatedly and vertically uplifted reached a critical height and finally splayed southward in the form of isoclinally overturned recline fold (F5) and thus gravitationally glided southward over the rocks of L H Belt after being detached along the Main Central fault during second tectonic phase of the Tertiary tectonic movements. The reclined limb of crystalline fold ultimately formed gravitational nappe sheet with inverted grade of metamorphism.

Most of the Himalayan geoscientists relate the main schistosity (S2) in the crystallines with the b tectonic transport direction related to the first phase of the caledonian deformation. However, Pande's investigations reveal that the socalled S2 schistosity is the relict (So) cleavage formed during the geosynclinal stage of

the MCCA basin. However, during the plutonic metamorphism and F1 folding caused development of S1 cleavage which was further accentuated, during the first phase of isoclinal folding (F2) to form S2 cleavage or schistosity in the crystallines. The S2 cleavage, during the successive stages of vertical uplift was modified to slip cleavage (S3) and Crenulation cleavage (S4).

Metamorphic history of the Himalayan crystallines

The metamorphic history of the crystalline of the MCCA belt has been meticulously deciphered by Pande and his associates. According to the hypothesis, the crystallines have suffered repeated metamorphism. According to this theory the Proterozoic-Ordovician metasedimentary prism (MCCAB), having a thickness of more than 8 km initially suffered Plutonic or Load metamorphism during the geosynclinal history of the basin, in caledonian orogenic cycle.

The sediments at a depth of 25000m or more were under 4 to 6 Kb hydrostatic pressure and a temperature of 400-600°C or 700°C, varying with depth of the burial. Under such PT conditions, the rocks of the MCCA zone suffered Plutonic metamorphism with development of fiberolite and andalucite, staurolite and garnet divided the central sedimentary prism into Katazone (deepest part having 4 to 6 Kb and 600°C T) and the Epizone of metamorphism (upper part having less than 4.5 Kb and 400°C T). The intermediate zone is marked by brown Biotite I and garnet I, which form the Mesozone of plutonic Chlorite II sercite II and rarely by biotite I. This marks the Episode I of the metamorphism.

The Plutonic metamorphism came to an end with the commencement of the Hercynian orogenic cycle, when folding movements caused Regional metamorphism—Episode II. During the folding movements, the high grade mineral continued to exist. However in the Mesozone Garnet II, Biotite II and Fibrolite made their appearance. The Epizone is marked by the appearance of Chlorite II and Muscovite II. At this stage axial planet cleavage S2 was also developed with formation of inverted isoclinal folds (F2). This phase of the regional metamorphism is called progressive stage of the Episode II.

The folding movements connected with the Hercynian orogeny, at a later stage, gave way to dislocation movements. The high grade minerals retrograded to form Chlorite III, Garnet got fractured and degenerated to biotite and Chlorite III with the release of ilmenite, sphene and iron oxide. This marks the end of the Episode II.

The PT conditions were further modified with the incoming of the Karakoram orogeny and vertical upliftment of the MCCA belt. In the progressive

stage of the Episode III the rock were mainly affected by migmatisation with the appearance of Orthoclase II, Quartz III, Muscovite III and Biotite II. During the dislocation movements that followed the second stage of folding movements, the minerals were further retrograded with appearances of Chlorite III & IV, Garnet II degenerated iron oxide and Quartz III got granulated to form mortar structure. This event marks the end of the Episode III.

The Episode IV of metamorphism related to the Tertiary orogenic movements is mainly related to metasomatic activity. Pande regards that Biotite III, Garnet III, Orthoclase III and Albite I are connected with migmatisation. The high grade minerals that appeared early were degenerated during dislocation movements, i.e. Chlorite IV and iron oxides which marks the end of the Episode IV of metamorphic history of the metamorphites of the Himalaya.

Migmatisation of the Himalayan crystallines

The hypothesis of pyro-metasomatic transformation of the Himalayan metamorphites into migmatites has been propounded by Pande in 1956 for the first-time. He successfully demonstrated that the socalled Quartz Porphyries of Ramgarh, Nainital District, are not the metamorphic derivatives of acidic flows but are the products of migmatisation. This conclusion is based on the field and laboratory evidences which has been acclaimed as an important piece of original work. This hypothesis is now followed by the Himalayan geoscientists.

Migmatisation, regional metamorphism and igneous action are the part and parcel of orogenic movements in the Himalayan region. The MCCAB crystalline during the end of the metamorphism were subjected to pyrometamorphic transformation into high grade migmatites (gneisses) with appearance of Quartz II, Biotite II, Garnet II, Plageoclase I, Orthoclase I, Muscovite I and Chlorite II, possibly related with ichors given out during the implacement of the Kawa Quartz-diorite (415 mg). This marks the 1st stage of migmatisation.

The second stage of migmatisation, according to Pande took place during the Hercynian tectogenesis and emplacement of Pandoh granite (339 my), Barkot granite (325 my), and Darlaghat garnite (240-238 my). The igneous bodies also supplied hot chemically active volatile gas and fluids and caused migmatisation (stage II), which is marked by the appearance of Quartz III, Biotite II and Orthoclase (microcline) I. The appearance of Quartz IV, porphyro-blastic Orthoclase II, Muscovite III, Biotite II and Garnet III mark the stage III of the migmatisation.

The final and stage IV of migmatisation of the crystalline rock occurred during the Tertiary earth movements. During the stage IV the metasediments were repeatedly migmatised at the end of Cretaceous and the beginning of the Eocene (75-55 my), during the Eocene (55-40 my), at the end of Eocene and the end of Oligocene (45-25 my) and finally during Miocene (25-10 my). The periods of migmatisation are closely related with the tectonic phase of Tertiary uplift of the Himalaya. The various tectonic stages of the Tertiary uplift were marked by igneous activity, e.g. Jaspa granite (52-40 my), Khardung volcanics (55 my), Narayan zone granite C. Napal (51 my), Ranibag granite (10-25 my), Mandi granite (24 my) and Badrinath-Makalu-Sob-chu tourmaline granite (25-10 my) and Dharmasala granite (20-38 my).

The process of pyrometasomatic replacement, according to Pande is a continuous process which leads to migmatisation followed by thermal metamorphism, iron metasomatic replacement and hydrothermal replacement.

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Pisharoth Rama Pisharoty

Pisharoty's basic training was in Physics. He had his training in research under C V Raman at Bangalore during the summer vacation of the years 1935 to 1940, and for a full year in 1941. Later he became a research meteorologist under the guidance of J Bjerknes at Los Angeles. He took his Doctorate from the University of California, Los Angeles in 1954, in a record time of one year.

Working as a vacation worker under C V Raman, at the Indian Institute of Science, Bangalore, he could publish three papers on optics, ultrasonics, and elasticity, in the Proceedings of the Indian Academy of Sciences.

Pisharoty wrote a book on X-rays in Malayalam in 1939, and bagged a prize. Pisharoty joined Meteorological Department, as an Assistant Meteorologist in January 1942.

Pisharoty carried out research relevant to weather forecastings. The papers published by him related to thermodynamic diagrams, thunderstorms, western disturbances, movement of monsoon depressions, easterly waves, orographic rain, heavy rainfall associated with monsoon depressions, etc.

Pisharoty worked under J Bjerknes at the University of California, USA on a couple of problems of the general circulation project. He brought out two notable reports, "*Some aspects of the geostrophic poleward flux of sensible heat*" and "*The kinetic energy of the atmosphere*". Pisharoty was awarded a PhD degree of the University of California for this work accomplished well within one year. His work there was perhaps responsible for several assignments of scientific importance made later by the World Meteorological Organisation and the International Association of Meteorology and Atmospheric Physics.

In 1959 Pisharoty was posted as Director, Colaba and Alibag Magnetic Observatories, Colaba, Bombay. He got involved in the study of geomagnetic storms, micoseisms, the electrojet over magnetic equator, the geomagnetic survey

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to determine the precise location of the magnetic equator over the west coast of India, etc. During this period he published papers on geomagnetic disturbances associated with nuclear explosions, micro-barograms and seismograms associated with supersonic bangs, width of the electrojet over south India, microseisms associated with tropical cyclones over the Bay of Bengal. Based on his past experience with civil aviation, he proposed a standard atmosphere for the tropics. The idea has caught up and R Narasimha and his group at the National Aeronautical Laboratory, has established one, based on more recent data.

In November 1962, he took charge as the Foundation Director of the Indian Institute of Tropical Meteorology. In that capacity Pisharoty was also closely associated with the International Indian Ocean Expedition 110E, 1963-1965. He had two scientific breakthroughs to his credit :

(i) That a significant portion of the water vapour content of the south west monsoon over the Peninsular India comes through evaporation over the Arabian Sea itself, particularly during an Active Monsoon period. This has been confirmed by an analysis of MONEX data by Dr Ghosh.

(ii) The warm sea surface temperatures of the west-coast of India-~ 30°C–has a significant role to play in the onset of the monsoon over the Konkan and Gujarat Saurashtra Coasts.

Pisharoty was actively associated as a member with the World Meteorological Organisation's Scientific Advisory Committee, which brought into existence the "World Weather Watch"–a WMO Programme by which several stations in the World received the meteorological data from all the National Meteorological Services, on a daily basis through a global network of telecommunications centres. New Delhi was one of the recipients of daily global data and also became one of the Weather Telecom Hubs.

As a foundation Member of the Indian National Committee for Space Research (INCOSPAR) Pisharoty was closely associated with Indian Space Research, ever since its first meeting in Feb 1962, under Chairmanship of Dr Homi Bhabha.

In 1968, Prof Sarabhai entrusted Pisharoty with the job of introducing Remote Sensing Technology into India. At that time the Senior Govt officials in India were very skeptic about the utility of this sophisticated technology for India's needs. Pisharoty's first job was to create an awareness among the people concerned, politicians and science administrators. This was done by lectures and

illustrated slides. A team of scientists was sent to USA for learning the technology as it was being applied to various disciplines like agriculture, forestry, hydrology, oceanography, geology, etc. They learnt much as knowledge was freely imparted.

On returning from this learning tour in USA, Pisharoty organised the first successful mission of early detection of coconut wilt-root disease by remote sensing from a Soviet aircraft, U S equipment and Indian scientists. He has found that one can get anything good done in India if he/she is not anxious to get sole credit for it.

In ISRO people call Pisharoty as father of Remote Sensing in India. As Director, Remote Sensing and Satellite Meteorology, at the Space Applications Centre, Ahmedabad during the period 1972-1976, he laid a sound foundation for Remote Sensing Technology in India. Now the facilities in India regarding Remote Sensing Technology–data collection, satellite pay load construction, data applications in several fields of National Development, are second to none in the world.

As a Member of the Joint WMO/ICSU Organisation Committee (JOC) for drawing detailed plans about the Global Atmospheric Research Programme. Pisharoty played a major role in accepting the MONEX as an integral part of the Global Atmospheric Research Programme. Some of the Members felt that the Indian Monsoon was a Regional phenomenon. Pisharoty convinced the committee that the Indian Monsoon was a result of global atmospheric process, and that it provided much energy for the global circulation over the middle latitudes of the northern hemisphere.

As a result of the studies conducted during the First Global Atmospheric Research Programme (1979), of which he was a member, Pisharoty has drawn a conclusion about the primary cause of the Indian monsoon. It is a delayed response to the inadequate transport of heat to the north Polar regions during the immediately antecedent winter months. As a Member of the Senior Scientists Panel, Indo-US Science and Technology Initiative Programme he played a significant role in the selection of cooperative projects on the Indian monsoon, conducted under the programme.

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Syed Zahoor Qasim

In his career, as a marine biologist and ecologist, Qasim has carried out investigations on a wide range of subjects related to his field. The subjects of research covered by him are as follows:

Pressure responses of marine animals

Qasim, with E W Knight-Jones[1], demonstrated that a large number of marine animals are sensitive to pressure changes. Some of these animals react to very small changes in pressure. These responses can easily be measured and provide a new concept of their depth regulation mechanisms.

Rearing of marine fish larvae in the laboratory

In the early fifties, it was considered most difficult, nearly impossible, to rear marine fishes in the laboratory from eggs to adulthood. Using two species of marine fishes and different kinds of food materials, Qasim not only succeeded in rearing but obtained a fairly high rate of survival[2,7].

Fishery biology

From his work on the ecology of shore fishes of Britain, Qasim developed new generalisations on their breeding cycles, which are applicable to marine animals in general[3-6]. He has also worked on the biology of freshwater fishes of northern Indian region and developed new concepts on their food and feeding habits, breeding behaviours and growth rates.

Fish physiology

Qasim carried out works on the respiratory physiology, haematology[8] and effect of temperature on the heart rate and provided explanation of some of these metabolic processes.

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Fish biochemistry

Muscle, liver and ovaries of 25 species of freshwater fishes belonging to 16 genera were analysed for protein, fat, moisture, ash, carbohydrate, phosphorus, calcium, and total iron. The nutritive value of the total fish of each species was determined.

Pollution of environment

Considerable work was carried out by Qasim on the pollution of rivers, estuaries and marine environment. Noteworthy among these are the river Kali, Cochin backwaters, Mondovi-Zuari estuarine system, coral reefs and the Arabian Sea and Bay of Bengal. Pollution caused by sewage, heavy metals and oil is of particular importance and he has enunciated a policy framework for controlling pollution.

Estuarine and marine hydrography

Different environmental characteristics such as solar radiation and its penetration, plant pigments, nutrients and several other features were measured on a seasonal basis and the role of these in controlling the production process of organic matter has been clearly demonstrated[9-11].

Primary productivity of environments

Qasim's works on this theme are cited extensively. The environments he investigated were tropical estuaries, coral reef, seagrass bed, atolls, sandy beaches, coastal waters and open ocean. He worked out the rate of production in each environment and the various factors governing the production rates[11-14].

Laboratory experiments on factors governing primary productivity

Several factors such as salinity and quality of illumination, were studied in the laboratory on phytoplankton. Growth kinetics and nutrient requirements of some phytoplankton organisms were worked out[13]. These experiments gave some explanation of the causes of phytoplankton blooms in tropical waters[9].

Energy pathways and food chain studies

Starting with solar energy, the other pathways through which the energy is produced and consumed in the marine and estuarine environments are phytoplankton, zooplankton, herbivores and carnivores. These have been worked out quantitatively[11,13]. From these studies it is possible to determine the potential fish production and also the exploited fish stocks in the marine environment. New pathways through decaying plant and animal materials (detritus) have also been established and these have been considered important for tropical waters.

Aquaculture

For the first time in the mid-seventies, the potential and scope of aquaculture in India was worked out. The importance of aquaculture in rural development was clearly demonstrated and it was shown that the yield of green mussel, when cultivated on ropes, is incredibly high. Similarly, the aquaculture potential of shrimps and other species was also demonstrated.

Pearl culture

Since the early fifties, India has been considering the possibility of producing cultured pearls in the country. More than fifty years ago, there used to be a flourishing pearl fishery in the Gulf of Kutch and Gulf of Mannar. However, no progress was achieved in the earlier years. In 1972, Qasim selected a site for conducting an experiment on pearl oyster farming and on the development of cultured pearls. Modern methods of raft culture were adopted for raising oysters. At the oyster farm the techniques of producing cultured pearls were developed and for the first time cultured pearls were produced in India. The Tamil Nadu government has now established a Corporation for the pearl culture industry.

Antarctic research

Qasim is considered as the founder of Antarctic research in the country. Polar science was non-existent in India till 1981-1982, when he led the first expedition to Antarctica and successfully landed the Indian team on the Antarctica continent on 9th January, 1982. After that he organised and sent six more expeditions to Antarctica. Within 10 years polar research in India has grown at a very fast rate and today there are nearly 30 or more institutions in the country working on the materials, data and samples collected from Antarctica. Nearly 700 research publications have come out from India during the last 11 years and several books have been written in different languages on Antarctica.

Oceanographic research

In his career Qasim has prompted ocean research in its totality and was responsible for building facilities for marine research in India including the growth and development of the National Institute of Oceanography (NIO) at Goa, procurement of three oceanographic research vessels and building the infrastructure for research and development in ocean sciences[15]. Thus, the works produced by him in various fields, indicate his overall command of the subject of oceanography.

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Bangalore Puttaiya Radhakrishna

Radhakrishna has spent a good part of his life in the study of the geology and mineral resources of Karnataka—formed mainly of some of the most ancient rocks belonging to the Archaean.

Closepet granite : Among the complex of ancient schistose rocks, Radhakrishna chose the Closepet granite for special study. His early work brought out the fact that the linear belt of granite extending for nearly 500 km did not form a single mass as shown in the geological map, but was made up of separate plutons of which a pink porphyritic member with porphyroblasts of pink to grey potash feldspar was the most characteristic member. Radhakrishna has put forward the view that the granite marks the site of collision of two discrete continental blocks, western and eastern, of early Archaean age. Great deal of interest has been generated in recent years on the petrogenesis of these granites and the role they have played in the development of granulites.

Neogene reactivation : Radhakrishna has from the start of his career taken special interest in the study of landforms. The hill masses of south India have long been considered to be the relicts of denudation of an ancient land mass unaffected by later earth movements. Radhakrishna questioned this concept, by identifying several erosion surfaces in southern India dating back to Cretaceous time. He argued that the Indian peninsula has been subjected to episodic uplift in geologically recent times. Western Ghats, paralleling the west coast of India has been shown to be the result of an upwarp in Miocene times. The ghats are shown to be precipitous edge of a youthful scarp. The antecedent character of the main rivers of the peninsula, the cases of river capture, the occurrence of water falls and deep gorges, have all been shown to be the effects of rejuvenation of an ancient land mass during the Neogene.

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Terrane evaluation : Radhakrishna has played an important role in unravelling the complex geological history of south India. In the light of the Plate tectonic theory, he has identified crustal elements of different ages and character, which have been brought together to form the present day India, which is a mosaic of different crustal blocks. The concept has helped in identifying the different stages of development of the Indian continent.

Metallogeny : Crustal evolution and metallogeny are aspects which have received close attention by Radhakrishna. He has demonstrated, taking specific examples from India, that metallogeny has closely followed crustal evolutionary trends through geological time. Simpler metal deposits like native gold, sulphides of copper, nickel, oxides of chromium are shown to be confined to the Archaean, following by more and more diversified and specialised deposits during later periods of earth history, much in the same way as organisms have evolved through time.

Mineral development : Radhakrishna has been closely associated with mineral development in the State of Karnataka. He has subscribed to the view that mineral resources, whether big or small, should be exploited to the best advantage of the State, and that mineral wealth will become a resource only when it is exploited and utilised. He has been critical of spending large amounts of money on projects aimed at exporting millions and millions of tones of raw ore without any processing whatsoever. He has been a champion of small scale mining which is environment friendly and benefits the people of the immediate neighbourhood. He has been responsible for opening up a number of mines in the State.

Groundwater : Hard rock areas of south India had remained neglected as unsuited for large-scale development of groundwater. Radhakrishna worked hard to change this attitude and demonstrated that even hard rocks can yield appreciable quantities of water, not only for domestic but even for irrigation purposes. A groundwater cell was created in the State of Karnataka, which has now grown into a big department devoted to developing the groundwater resources of the State and meeting the growing needs of the people for water. Tremendous interest has been generated in the development of this resource, with the result there is the danger of over-exploitation.

Geological Society of India : The need for an organisation solely devoted to the promotion of earth science studies in the country was seriously felt and Radhakrishna took a leading part in the organisation of the Geological Society of India. The idea took final shape and a society was formed and registered in 1956. In order to promote the objective of the Society, a journal was started, providing

an outlet for the publication of important research carried out in geology and closely related fields. Under his editorship, the journal has attained an international status. Radhakrishna functioned as the Secretary of the Society for the first fourteen years and as Editor of the Journal for the next fifteen years, and is now (since 1992) President of the Society. No other work has given him greater satisfaction and a sense of fulfillment than the work he has been able to do for the Society.

Gold mining : Radhakrishna has been lately interested in the development of gold mining industry in India. He has brought out a comprehensive study entitled *Gold–the Indian scene* jointly with L C Curtis. The reason for India being at the bottom of the world table in gold production is analysed and a strong plea has been put forward for the resurrection of the industry. The potential that exists for development has been emphasized.

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Ravipati Raghavarao

Ionisation density ledge

It is well known that a layer of the ionosphere is formed out of two competing processes: (1) the ion-electron pair production rate by the solar EUV radiation and (2) the loss processes. The primary loss processes for the F_2 layer formation are the chemical recombination of O^+ ions dominating in the bottom side and the plasma diffusion along the earth's magnetic field lines dominating on the topside of the layer. The altitude at which these two loss processes are nearly equal, lies the maximum plasma density of the F_2 layer. Above that altitude (usually 300 km) diffusion rate increases and ion-electron production rates decrease, both exponentially, and therefore no layer formation was expected. However, in the equatorial ionosphere a sharp dome shaped layer is formed on certain days and it is known as Ionisation Ledge phenomena. It is dome shaped in latitude, because it is aligned to the earth's magnetic field lines.

Raghavarao and his students measured the ledge characteristics by acquiring ISIS satellite data in India—its structure, shape, dynamic behaviour of its height, variation with local time and its association with other equatorial phenomena known as the counter electrojet located a few hundred kilometers below the ledge heights[1,2].

Raghavarao explained the formation of the Ledge. According to him, the neutral temperature and density are increased at the ionisation density crests of the well known equatorial ionisation anomaly (EIA) in the F_2 region, compared to those at the trough of EIA lying in between the crests and over the dip equator. The formation of such anomalous distribution of neutral temperatures and densities in turn inhibit or even stop the ambipolar diffusion of plasma, pumped up by the Fountain effect from the *F* region close to the dip equator, resulting in plasma density accretion at the top of the field line passing through the EIA crests, and thus a dome shaped layer forms[3]. Thus the ledge formation is governed

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by the plasma and neutral dynamics and their mutual interaction. About twenty years later, the neutral temperature anomaly similar to EIA, that Raghavarao hypothesized to explain the Ledge formation, was discovered by Raghavarao himself[4].

Equatorial electrojet and the counter electrojet

Raghavarao conducted a number of rocket campaigns and measured *in situ* winds and electric fields by releasing Na, Ba and other chemicals in the height region of 100 to 300 km in the region of equatorial electrojet and above. Simultaneously, he developed numerical models of the equatorial electrojet (EJ), equatorial ionisation anomaly (EIA) and on the nonlinear simulation of the Rayleigh-Taylor Instability (RTI) in the F-region. Raghavarao incorporated the measured winds in the models to show the wind effects in those phenomena and interpreted the outstanding problems.

One of the enigmatic problems of the equatorial region was why the electrojet reverses its daytime current flow from eastward to westward on certain days. This phenomena is known as Counter Electrojet (CEJ).

In a series of papers, Raghavarao and his student showed that zonal winds and the vertical shears in them cannot alter the daytime current flow significantly at the centre. Zonal winds however, can alter dramatically the latitudinal width of the jet and thus alter the structure and shape of the jet. Severe structural changes in the meridional current whorls, existing on the south and north sides of the main zonal current distribution, were shown to be effected by the meridional winds and the shears in them[5].

Raghavarao and his group, by releasing barium (Ba) and strontium (Sr) blobs by rockets, measured vertical winds of unexpectedly significant magnitude (20 m/s), in addition to horizontal winds in the electrojet region[6]. Using these measured values in the electrojet model, he and his student gave the first convincing interpretation of the counter electrojet (CEJ) phenomena[7].

Post-sunset plasma instability (spread-F) in the equatorial F_2 region

The height region of 80-120 km is the seat of many interesting and complex processes both for the structure and dynamical behaviours. The mesopause lies at 90 km. Vertical shears in the horizontal winds are common occurrence in that region. Electric fields of different scale sizes, particularly of planetary scale size are generated by the winds of tidal origin in that region. These electric fields are communicated to higher altitude through the highly conducting earth's magnetic field lines and cause, in turn, plasma convection by the $E \times B$ drift velocities at the

altitudes of ionospheric F-layer and above. At the sunset time E-layer conductivities decrease drastically and electric fields are generated at F-layer altitudes.

Employing the metallic Ba and Sr vapour release technique onboard the rockets, Raghavarao chose to investigate the causative mechanism of a plasma instability known as equatorial spread-F (ESF) in the F-layer that occurs at sunset on certain days. Barium and strontium release technique has a limitation, that the releases should take place after ground sunset but at a fixed solar zenith angle (around 18° 40′ LT) to have the released clouds to be sunlit in order to photograph them from ground stations and that time should coincide with the occurrence time of ESF which was unknown on any day, until it occurs. Raghavarao conceived of a method, based on ionograms at three different latitudes (Ahmedabad, Waltair and SHAR) in the EIA region of predicting the occurrence of ESF on a particular evening and he successfully launched the rockets at the onset time of the ESF. Among a number of results he obtained from these rocket campaigns, two results stand out clearly as new. He detected the presence of a large scale (of 10-20 km size) structure of an irregularity in the electric fields around 200 km altitude. Another new result is the presence of vertical winds. Both of them are found to be nearly at the onset time of ESF[8,9].

Based on these experimental evidences Raghavarao and his student developed a theory to show how the vertical winds, depending on the polarity, can either trigger or annul the growth of plasma instability[10]. Later he and his group described the ESF growth by developing a computer code for the nonlinear effects of vertical winds on the plasma instability growth rate and its propagative effects to higher altitudes. His efforts thus explained the enigmatic problem of why the post sunset ESF phenomena occurs on one day and does not occur on another day with similar solar activity and ambient electric field conditions[11].

In addition, Raghavarao proved by the above experiment and theory, for the first time, that the dynamical behaviour of the neutral atmosphere plays an important role in destabilising or stabilising the F-layer at low latitudes. Earlier to his work, ESF at low latitudes was thought to be caused by an instability (RTI) in plasma itself, because of its sharp density enhancement in vertical direction supported against gravity by the earth's horizontal magnetic field lines near the dip equator.

More recently, Raghavarao discovered an anomalous distribution of neutral temperature and zonal winds similar to and associated with the ionisation anomaly (EIA) at low latitudes at the altitudes of ionospheric F_2-region. Also he

discovered a systematic structure of vertical winds with latitude, with a downward polarity over the dip equator at pre-midnight hours in solar maximum period when ESF phenomena is known to be occurring frequently.

Additional theoretical work on some outstanding problems

A number of vertical electron density profiles were measured by others at different local times from Thumba Equatorial Rocket Launching Station (TERLS) located near the center of the Equatorial Electrojet (EJ). The profiles revealed that the density at 100 km altitude increases by a factor of 2 to 5 from a minimum at local sunset to a maximum around midnight. In addition an electron density valley was observed around 120 km height.

By solving the continuity equation including the term due to the vertical ion motion, expected to be present at the electrojet centre, Raghavarao and his group explained the plasma density enhancements at 100 km as well as the valley formation at 120 km altitude in the nighttime, when the solar EUV radiation–the main ionising source is absent[12].

The equatorial ionisation anomaly (EIA) has been investigated by several workers all over the world. One of the outstanding problems was why the EIA develops earlier during the day in solar minimum period than during solar maximum period. By solving the continuity equation for electrons, Raghavarao and his group explained it as due to the lower neutral temperatures and densities at F-region altitudes during solar minimum period compared to solar maximum period. Ambipolar diffusion of plasma along the earth's magnetic field lines is inversely proportional to the neutral density and temperature and this property was shown to explain the earlier formation of the EIA during the day in solar minimum period than during solar maximum[13].

Discovery of equatorial temperature and wind anomaly (ETWA)

The data from WATS (Wind and Temperature Spectrometer) and LP (Langmuir Probe) instruments onboard the DE-2 (Dynamic Explorer-2) satellite in the low latitude region near the perigee altitudes (300-450 km) were used to detect this anomaly.

Raghavarao showed clear evidence, for the first time, of an equatorial anomaly in the neutral gas temperature and zonal winds, similar to the already known equatorial ionisation anomaly (EIA). The neutral temperature variations with latitude around 300 km altitude and above, show a minimum over the dip equator flanked by two maxima on either side at about $\pm$ 20°. The zonal wind variation with latitude, on the other hand, reveals a maximum over the dip

equator, not on the geographic equator as all wind models predict, flanked by two minima on either side. The minimum in the temperature and the maximum in the zonal winds are collocated with the trough of the EIA; while the maxima in the temperature and the minima in the zonal wind structure are collocated with the crests of the EIA. Thus the characteristics of this newly found equatorial temperature and wind anomaly named ETWA, provide the first evidence for the ion drag effect of the EIA on the neutral motions causing redistribution of energy. The magnitude of variation in the temperature and zonal winds associated with ETWA was found to be variable with local time but at certain times, is larger than 100K and 100 m/s, respectively[4].

The discovery of the temperature anomaly and its crests being collocated with the EIA crests provided evidence to the hypothesis made by Raghavarao about twenty years earlier to this discovery, that such higher neutral temperature enhancements need to exist for explaining the formation and sustenance of ionisation ledge in the equatorial topside ionosphere[3].

Vertical winds in the premidnight hours

By analysing WATS data on vertical winds, Raghavarao showed clear evidence of a latitudinal distribution of the vertical winds at premidnight hours, revealing a structure coherent with the EIA and ETWA in the height region of 300-450 km at low latitudes.

The vertical winds are downward around the dip equator collocated with the temperature maximum and they are upward around the temperature crest regions. From the measured neutral densities measured by a mass spectrometer onboard the same DE-2 satellite and the temperatures by WATS, Raghavarao showed that the latitudinal distribution of pressure at any altitude in the 300-450 km height region is nearly identical to the temperature distribution and reveals two crests with a trough in between them. On the basis of this experimental evidence of a formation of two pressure ridges on either side of the dip equator, he explained the observed vertical winds by predicting two whorls of circulatory meridional winds near each of the crests of the pressure bulges. Thus, EIA crests give rise to temperature and pressure crests or ridges on either side of the dip equator by the redistribution of energy. They in turn become new sources of momentum in the meridional plane in the equatorial thermosphere. Thus he predicts a completely new dynamical coupling process that occurs, whenever the EIA formation of the equatorial ionosphere intensifies, between the ionosphere and thermosphere at low latitudes[14]. It is important to note here that the vertical wind hypothesis he made earlier to explain the vagaries of occurrence of the post-

sunset plasma instabilities in the F_2-region, finds ample justification in the detection of systematic structure of vertical winds with downward polarity over the equator coherent with ETWA. These new evidences and interpretations require conformation by systematic measurements, in future, simultaneously on both ionosphere and thermosphere of the equatorial region.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Rama

Rama started his research career as a student at Tata Institute of Fundamental Research, Bombay in 1950. He took up the construction of a 500 kV Van de Graff generator, and was joined soon by other colleagues, and subsequently completed the construction of a 1 MeV cyclotron as well. Later, he switched over to the study of cosmic rays using nuclear emulsions under the guidance of Bernard Peters. High energy cosmic ray interactions, production of mesons and their interactions formed his field of work for a few years. His accurate measurement of distortions of straight tracks of high energy particles led to the discovery of 'spurious scattering' in nuclear emulsions.

Once again, at the bidding of Bernard Peters, Rama undertook study of cosmic ray produced radioisotopes in the atmosphere. As per Peters' suggestion, he undertook simultaneous measurements of several radioisotopes (along with others), and for the first time brought out the usefulness of these studies in unravelling some characteristics of atmospheric circulation. This formed the mainstay of the award of PhD degree to him. Subsequently, on his own, he made several contributions in this field. While at it, he digressed to several different, but allied areas also.

Rama and D Lal analysed world data on atmospheric radiocarbon. Their analysis led to the discovery of seasonal variation in exchange of tropospheric and stratospheric air at tropical and high latitudes. In particular, it became evident that during spring time when stratospheric air is exchanging with tropospheric air at high latitudes, the mixing of tropospheric air between the high and low latitudes is minimal. This provided an explanation for the fact that ^{90}Sr spurted down from the stratosphere to the troposphere at high latitudes during spring does not spread to tropics and gets rained out at high latitudes itself.

Rama conceived the idea that measurements of radon in the air over the Arabian Sea might provide an ideal tracer for the flow of monsoon air. The

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underlying idea is that the air, south of equator, should be bereft of radon over the Indian Ocean, and any air coming from East Africa over to the Arabian Sea should be rich in radon. By making measurements of radon in air over the Arabian Sea during monsoon season, it should be possible to delineate the circulation. He undertook several cruises over the Arabian Sea, and found that the underlying thinking was indeed correct, and he was able to demonstrate the usefulness of radon measurements in delineating the monsoon circulation. His idea about using radon in characterising the low level inversion over Rajasthan and north Gujarat during the monsoon still needs to be attempted.

Rama has also delved into geochronology using mass spectrometric as well as track etching techniques. He provided the first set of K-Ar dates for the Deccan traps.

Rama was intrigued by the fact that a substantial part of radon generated from decay of radium in crystalline minerals is able to emerge out of them. He, along with W S Moore, made a thorough study of the phenomenon, and has come out with a likely explanation. By a set of ingenious experiments, he was able to show that most minerals have nano-wide planar fractures in their bodies and also at grain boundaries. Any radon entering these fractures is able to diffuse out of the network, which these fractures form.

Over the years, Rama has been getting more and more interested in various aspects of 'water resources of India'. Immediately after hearing about Münnich's work on environmental and artificial tritium in evaluating groundwater recharge, Rama introduced the same techniques in India where they have now found the widest applications. While working on a project related to nuclear Agro-Industrial Complex of the Department of Atomic Energy in western Uttar Pradesh, he conceived of a possibility of storing surplus flood waters underground. The concept makes good sense in Indian setting. The idea is to lower the water table in narrow belts along the seasonal (non-perennial) streams by heavy pumping during dry period. It is hoped that when streams go in spate during rainy season, there will be enough infiltration of water through their sandy beds as to refill the aquifer. A pilot project was undertaken to test this idea, with the help of Groundwater Department of UP state in 1988-89, on 5 km stretch of Hindon near Saharanpur. The project demonstrated that the concept was quite valid. There was no problem at all for replenishing the water table up by 5 meters. However, due to administrative problems, the project could not be extended to find out the full

potential of the concept. May be, the water can be drawn so as to lower the water table by 10-15 meters, which may well replenish during rainy season. Rama regards this idea as potentially useful.

Rama has made short forays into various other areas. He thought that characteristics of mutations caused by heavily ionising particles (like alpha particles and fission fragments) may be quite different from those caused by chemicals or X-rays. An experiment carried out, using fission fragments and alphas from ^{252}Cf source, did indeed yield some surprising results.

Rama has speculated on the consequences of the most massive hydrological alteration being carried out in India, i.e. of extensive and intensive development of irrigation in India. Irrigation leads to introduction of water vapour into the air at the expense of run-off to the sea. Rama speculates that this might improve the rainfall in the country.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Ram Gopal Rastogi

Rastogi started his research career in 1951 under the guidance of late K R Ramanathan. His initial studies were concerned with the propagation of radiowaves during solar eclipses, culminating in a detailed report on the subject. He was responsible for the installation of the world famous ionospheric station at Ahmedabad which continued uninterrupted operation over the period 1953-1980 and is credited with many discoveries on the ionosphere at low latitudes. The geomagnetic control of the quiet day as well as disturbed day variations in the ionosphere were among the major problems tackled by him during earlier years. His critical investigations of the global data on f_0F_2 led to the hypothesis of equatorial fountain theory of the F-region. His studies on the lunar tides on f_0F_2 not only indicated a very close relationship between geomagnetism and ionosphere at low latitudes but also predicted the longitudinal inequalities in equatorial electrojet currents later verified by rocket experiments in India and Peru.

In 1963, Rastogi organized and established another ionospheric research station at Thumba at the advice of late Vikram A Sarabhai. In a short span of five years, this station made a host of new discoveries on equatorial electrojet, plasma irregularities, dynamical and storm effects in the equatorial ionosphere. These data led to the discovery of the new phenomenon of kink at equatorial ionosphere.

Rastogi has contributed significantly to the phenomenon of counter-electrojet regarding its latitudinal and longitudinal solar cycle effects. He was the first scientist to show a very intimate association between the variations in the geomagnetic and ionospheric conditions at the equatorial electrojet region with the interplanetary magnetic field, thereby giving rise to a new field of ionospheric-magnetospheric coupling.

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With the emergence of satellite era, Rastogi took up the problems of satellite communications by studying the phase and amplitudes of radiowaves radiated from low orbiting as well as geostationary satellite on HF, VHF and UHF bands at different latitudes and longitudes. He was responsible for the installation and operation of one of the most sophisticated satellite receiving stations at Ootacamund in collaboration with the National Bureau of Standards of USA in 1975-76 at the time of SITE experiments by ISRO of India and NASA of USA and obtained a unique set of data on electron content and scintillations at low latitudes, not duplicated anywhere else in the world.

Rastogi has always been an advocate of university partnership in research plans of national research laboratories and had helped to develop research activities at a number of university centres like Tiruchirapalli, Madras, Udaipur, etc. During 1975-76, he organized a national project on satellite radio communication studies involving a number of universities.

Since 1980, Rastogi has been Director of the Indian Institute of Geomagnetism with its headquarters in Bombay and field observatories distributed all over India. His main effort has been to develop this institute into a national centre for research in geomagnetism and aeronomy utilizing the special environment of India for using geomagnetic method for studies on solid earth and space physics.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Amalendu Roy

Roy was educated at Calcutta and Dacca Universities, and at the Colorado School of Mines, USA. He has served the Geological Survey of India; Indian Institute of Technology, Kharagpur; Oil and Natural Gas Commission, Dehradun; National Geophysical Research Institute, Hyderabad; and the United Nations (as an expert in applied geophysics in Brazil and Nigeria), and is currently a Professor of Geophysics, University of Ife, Nigeria. He is a specialist in exploration geophysics and has had extensive experience in teaching, research, field surveys and management in this discipline. The more important of his research contributions are discussed below in brief.

Geophysical interpretation and field techniques

In the pre-digital days of manual computation, an optical device was designed for determining the gravitational and magnetic fields for three-dimensional bodies, based on the fact that all these three fields obey the inverse square law[1]. Through theoretical analysis and laboratory modelling, a procedure was established for the quantitative interpretation of self-potential measurements over sheet-like mineralised veins. The relaxation method was applied for upward continuation of gravity and magnetic data. A simple integral transform was devised for handling gravity and magnetic anomalies caused by bodies that are neither point poles nor infinitely long line poles[2]. In general, this transform converts a three-dimensional field into a two-dimensional one without altering the essential body parameters. Two new interpretation techniques were developed for use in telluric field and self-potential surveys[3]. Methods were developed for the interpretation of gravity and magnetic data collected over uneven topography, in boreholes and over inclined surfaces. Extensive theoretical, analog model and field investigations were carried out towards the development of the two-electrode array as a more efficient tool in resistivity and induced polarization surveys[4,5].

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Important new concepts

The problems of non-uniqueness in geophysical interpretation was investigated in depth and detail[6]. The gravity and magnetic methods are non-unique, not because these fields are derivable from a scalar potential function, as is generally believed, but because the unknown parameters of the ground greatly exceed the independent observables. Geophysical methods, including the seismic methods, can yield unique interpretation only when the number of unknowns is reduced drastically to a manageable level by using extraneous information on the shape and physical property of the sources.

The method of analytic continuation was originally developed for application only to gravity and magnetic data in oil exploration. This position was substantially expanded with the following new contributions[3,7-9]: (i) The technique can be applied to other geophysical methods as well, such as, self-potential, low frequency or dc telluric, and electromagnetic data in non-conducting media. (ii) The method is more generally useful in exploration for hardrock minerals rather than petroleum, because the shapes of hardrock ore bodies are usually such that the onset of oscillations in the downward continued field occurs near their top. (iii) The region of validity for convergence of the continued field was formally established. (iv) The problem of analytic continuation of general electromagnetic fields—for arbitrary frequency and ground conductivity—was solved for the first time.

In the field of direct currents, a new theorem was formulated[10] that expresses the measured signal, a potential difference, for an arbitrary ground as the sum of the dipolar contributions from the volume elements of the entire space. This allows one to examine an observed resistivity anomaly in terms of the constituent fractions originating in different ground compartments, such as the target itself, host rock, overburden, etc[11]. This also led to an objective definition and determination of the depths and radii of investigation in various resistivity and induced polarisation arrays in ground surface as well as logging work[12,13].

A general formula, supported by a practical computational procedure, was derived for transforming an observed magnetic map for any component, at any latitude and for any given direction of magnetisation into another, for which any one or two or all the three parameters differ. Baranov's reduction to pole and Lourence and Morrison's computation of vector magnetic anomalies in an area from measurements on a single component in that area are but two particular cases of this general transformation. Three new magnetic transformations were specifically brought out: (i) reduction to equator, (ii) orthogonal reduction, and

(iii) elimination of remanence. All these transformations simplify magnetic interpretation by promoting symmetry and zero lateral shift[15].

Geophysical well logging

Various kinds of focussed resistivity logging devices have been and are being widely used all over the world for nearly 35 years. Extensive theoretical and analog model studies[15], however, demonstrate conclusively that focusing has no inherent advantage and that the response of a focussed tool—which is considerably more expensive—can be synthesized rather closely from that of the conventional two-electrode resistivity logging sonde. Any focussed array has a reciprocal that is unfocussed but has exactly the same response.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Supriya Roy

Roy's research contributions, essentially in the field of economic geology (ore geology), are significant in their holistic approach, that integrated the development of ore deposits to different facets of lithospheric evolution. In the early part of his research career, he characterized the vanadium-bearing titaniferous magnetite ore deposits hosted in mafic igneous rocks of Mayurbhanj District, Orissa, and developed a genetic model for these deposits that stood the test of time. His researches on massive sulphite deposits hosted in volcanics in Bathurst-Newcastle districts, New Brunswick, Canada, brought into focus many outstanding problems that induced further research by others, categorizing these as metamorphosed volcanogenic back-arc type deposits.

The major thrust in Roy's research efforts, however, lay in detailed characterization and genetic modelling of the widespread manganese deposits (manganese oxide ores and manganese silicate rocks) of diverse types occurring in different geological formations of India covering a wide range of time from c. 3000 to c. 775 million years in the Precambrian geological history of this subcontinent. Since these deposits are distributed over a very large portion of the Precambrian time-domain, attendant with the various stages of atmospheric, hydrospheric and lithospheric evolution and the deposits are both metamorphosed and unmetamorphosed, Roy planned his research programme primarily with two objectives: (a) correlation of the genetic models developed by him for the manganese deposits to the corresponding geological and geochemical environment, and (b) determination of petrogenetic evolution of manganese-rich sediments with varying bulk compositions during different grades of metamorphism. These studies involved a thorough characterization of the geological and tectonic setting of the manganese deposits and their petrographic and geochemical attributes. All these deposits have been established to have

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developed in stable shelf regions with no direct volcanogenic contribution. Only in two cases, in the Sausar Group (metamorphosed to amphibolite facies) and in the Eastern Ghat sequence (metamorphosed to granulite facies), restricted formation of Mn-carbonate took place in anaerobic/dysaerobic condition; otherwise all other deposits including a major part of those in the above sequences demonstrate that Mn-oxide/hydroxide represent the progenitors indicating deposition in oxygenated condition.

Roy and his associates established the diagenetic pathway for the initially deposited manganese oxide/hydroxides within determinable physico-chemical constraints in respect of the unmetamorphosed deposit of Penganga Group (c. 775 Ma), India. They also defined, through detailed petrogenetic studies of metamorphosed manganese deposits of India (particularly the lower Proterozoic Sausar Group) and calibration to the thermodynamic indicators determined from co-metamorphosed host rocks, the metamorphic reactions in Mn-rich sediments of varying composition elaborating the metamorphic pathways in given physicochemical constraints. The first viable quantitative petrogenetic grid for Mn-oxides and Mn-carbonates (poor in silica) was constructed by Roy and his co-workers, integrating petromineralogical, chemical and thermodynamic data on the metamorphosed manganese deposits of India in particular and on those from elsewhere in the world. This grid very effectively illustrates P-T-X pathways of manganese-rich sediments in natural conditions, varying from diagenetic reconstitution to amphibolite grade of metamorphism. Roy and his associates also developed a petrogenetic classification for the metamorphosed manganese deposits of the world based essentially on the structure constructed for the best-studied Indian types with all their diversity. In this process, it was possible to determine the nature of the precursor manganese phases prior to diagenesis and metamorphism.

Manganese, in its different phases, is established as an excellent geochemical indicator of aerobic-anaerobic/dysaerobic condition of the atmosphere/hydrosphere system through geological history and the Mn/Fe ratio of the phases reflect specific genetic processes. Therefore, the recognition of the pristine precursor manganese phase in the pre-metamorphosed manganese-rich sediments in Indian deposits led to the understanding of their precise depositional environments. Such studies on metamorphosed manganese deposits carried out by Roy and his co-workers established on one hand the specific geochemical conditions under which manganese was originally deposited as different phase in the sediments and on the other indicated the nature of evolution of the

geochemical environments in the atmosphere/hydrosphere system through the long time-span (c. 3000 to c. 775 Ma) in the Precambrian, in different stages of which the Indian manganese deposits were formed.

As global leader of the UNESCO-sponsored International Geological Correlation Programme (IGCP) Project No. 111 (Genesis of manganese ore deposits : 1978-1985) and Project No. 226 (Correlation of manganese sedimentation to palaeoenvironments: 1986-1990; jointly with B R Bolton, Adelaide University), Roy was deeply involved in international collaborative research efforts on the genesis of manganese deposition in diverse geological settings in different parts of the world with the ultimate objective of correlating these deposits to some optimum geological parameters. The knowledge thus gained, coupled with his research background in the Indian context, enabled Roy to synthesize geological and geochemical data on different types of manganese deposits of Precambrian and Phanerozoic age on a global scale. Critically interpreting the existing data-base on these deposits (many of which he studied personally), he classified them under a few specific genetic models that are intrinsically related to the different stages of lithospheric evolution. Consequent to this establishment of a genetic classification, Roy proceeded to determine the global metallogenesis of manganese as an expression of the changing palaeoenvironmental scenario with time.

To complement his studies on ancient manganese deposits, Roy undertook research programmes on ferromanganese nodules and micronodules occurring on different types of sediment substrates in modern ocean basins. These studies by him and his co-workers shed new light on the environments and processes of deposition and post-depositional changes of these deposits.

The holistic approach of Roy towards the environments and processes of formation of manganese deposits as an expression of the dynamic global geological scenario is amply demonstrated in the comprehensive analysis incorporated in a large number of research papers and in his book on manganese deposits.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Ashit Baran Roy

Roy has made significant contributions in several interdisciplinary fields to the understanding of complex geological history of different regions, such as Singhbhum (Bihar), the Caledonides of Sweden, and the Aravalli Mountain of Rajasthan and the Himalayas.

Roy's early research activities included study of interrelationship between deformation and metamorphism in central Singhbhum, Bihar. Working along a strip between the Singhbhum granite in the south and Dalma volcanics in the north, Roy worked out a time frame for correlating stages of mineral growth (recrystallisation as well as neomineralisation) with different phases of folding deformation. The extensive retrogression noted in the rocks was found to be the result of diaphthoretic metamorphism during the later shearing (thrusting) that followed.

Roy initiated detailed structural analysis of the type of Aravalli rocks in the south-eastern Rajasthan. He and his coworkers were the first to describe superposed folding in the rocks. On the basis of detailed mapping in areas around Udaipur, Jhamarkotra and Zawar, Roy worked out stages of complex deformation history resulting from polyphase folding of rocks. The very complex deformation recorded in the region was found to be comparable in style, geometry and sequence with that noted in central Rajasthan, between Nathdwara and Amet.

Roy made fundamental contribution to the evolution of slaty cleavage fabric on the basis of his studies on the 'Huns-ruckschiefer' slates of western Germany and Belgium. He described different stages of slaty cleavage evolution in rocks during diagenesis and the lowest grade of metamorphism associated with transformation of shale to slate.

The work in collaboration with S K Ghosh and Bjorn Troeng, in the Seve Nappe at Are in the Swedish Caledonides helped in elucidation of a complex deformation history, resulting from a number of fold phases. The development of

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folds was during different stages of thrusting. There was evidence to prove presence of a phase of folding which was pre-thrusting in age.

Roy, in collaboration with his research colleagues (B S Paliwal, P R Golani, D K Nagori, and B R Bejarniya) erected stratigraphic succession of the Aravalli rocks on the basis of detailed study of field relationship of the rocks in the region around Udaipur. He identified features which helped in recognising unconformity between the Aravalli Supergroup and the basement gneissic complex. Detailed mapping in regions of relatively low strain, led Roy to recognise pre-Aravalli tectonic elements at an angle to the Aravalli tectonic grains. Discovery of rocks as the possible ancient soils marking weathering surfaces is very significant in this context.

The Aravalli Supergroup, according to Roy's studies were deposited in 3 stages on rifted basins which formed ensialically on Archaean basement rocks. The basin evolution which marked an early phase of mafic volcanicity followed deep peneplanation of the basement. The attributes of the basin fills indicated a continuous change in depositional environment, suggesting a strong interplay of tectonism, erosion and sedimentation. The influence of tectonics is clearly implied in the recorded stages of sedimentation. Roy modelled a very special tectono-sedimentary situation which controlled the growth of phosphate stromatolites in this part of the Aravalli sea.

On the basis of inter- and intra-belt correlation of the Aravalli Supergroup rocks and their facies distribution, Roy proposed simultaneous opening of the Aravalli basins as ensiallic FRR rifts with failed arms. The triple junctions of the basin openings have been presumed to be located at around Chittaurgarh and Nathdwara, respectively. The emplacement of ultramafic rocks, according to Roy, was during the deepening of the rift basins in the west (in the Jharol belt), the latter becoming the receptacle of carbonate-free shale deposits with minor bodies of quartz arenite. The evolution of shallow and deep sea facies depositional basins are analogous to the ephemeral development of the eugeosynclinal and miogeosynclinal couplets as developed during the earliest Proterozoic recorded elsewhere.

Stratigraphic correlation of rocks and the palaeogeographic modelling led Roy and his coworkers (P R Golani and B R Bejarniya) to postulate that the granitic rocks (the Ahar River granite, Udaisagar granite, etc.) which were earlier thought to be intrusive into the Aravalli 'system', are the basement rocks, which not only floored the Aravalli sea but also supplied sediments during the basin fillings. Roy refuted suggestions of a new, supposedly Archaean, Bhilwara Group

(or Supergroup) as the basement unit underlying the Proterozoic rocks. He and his coworkers (M K Somani and N K Sharma) conclusively proved that the proposed unit was a time-transgressive collage of rocks.

According to Naha and Roy, the basement rocks—the Banded Gneissic Complex of Heron have been involved in ductile deformation during the folding of the Aravalli rocks. This made the identification of the basement-cover interface extremely difficult over large parts in central Rajasthan.

The work by Roy and his collaborators led to discovery of 3.3 Ga Archaean rocks in the pre-Aravalli basement, named as the Mewar gneiss. Besides the Sm-Nd isotope dates (in collaboration with K Gopala, J D Macdaugall and A V Murali) which also recorded mafic magmatism at 2.83 Ga, the polyphase evolution of the Archaean basement (the Mewar gneiss) is also proved by zircon single crystal dates (done in collaboration with Alfred Kroner, and Michaeal Wiedenbeck and J N Goswami). The date of cratonisation of the Archaean basement is recorded to be around 2.5 Ga.

Detailed mapping and geochemical studies by Roy and his colleagues [Rajani Upadhyaya, B L Sharma (Sr), and B L Sharma, (Jr)] helped in characterising a part of the Mewar gneiss as remnants of greenstone sequences in a 'sea' of gneisses and granitoids of different composition and character.

Studies around Kishengarh, Distt Ajmer, led Roy and his coworker (K Dutt) to postulate a tectonothermal model of evolution of the nepheline syenite close to the Delhi-pre Delhi boundary. The nepheline syenite pluton, which occur as an elongate dome structurally underlying the newly defined Kishengarh Group (and correlated with the Lower Aravalli Group), has been presumed to have evolved by partial melting of deep crust or upper mantle. The diapir subsequently rose up to the depth corresponding to the amphibolite facies metamorphism, during he opening of the Delhi basins in the west.

'orking in the Delhi fold belt, Roy and his colleague (A R Das) correlated climax of the first (regional) metamorphism with the movements during the first two phases of folding. The synorogenic granites corresponding to these events were emplaced at around 1.45 Ma. The later thermal events in the Delhi fold belt took place at Ca. 0.85, when a series of granitic bodies intruded the belt.

In the central Kumaun Himalaya, Roy and Valdiya proposed a new model of tectono-metamorphic evolution of the great Himalayan thrust sheets. The Vaikrita Group has been described as a huge lithotectonic slab bounded by moderately inclined MCT in the south and steeply dipping (Trans-Himadri)

Maleri thrust in the north. The Munshiari Unit, which occur to the south of the Vaikrita Group is a severely tectonised and drastically condensed thrust slab. The Vaikrita rocks show extremely intricate internal deformation resulting from polyphasal folding and repeated transposition of foliation planes. It has been suggested that the episodic uplift of the Vaikrita Group was due to shifting of the thrust movements by relay from the MCT to the Munshiari Thrust and other minor thrusts of the schuppen zone. A part of the uplift has been correlated to the diapiric rise of the anatectic granites.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Ajit Kumar Saha

As a Professor of Presidency College, Saha has carried out extensive research on various aspects of petrology, geochemistry, Precambrian stratigraphy and geomathematics.

Saha has carried out extensive research in three distinct fields: (i) petrology, geochemistry and Precambrian crustal evolution, (ii) application of statistical techniques in problems of petrology and mineral exploration, and (iii) problems of the environment, particularly those relating to air pollution, water pollution and groundwater management.

Saha's important contributions are discussed below in brief.

He carried out intensive studies on the history of emplacement of three granitic plutons in SE Ontario, Canada, using structural, petrological and decrepitometric methods. In this connection, he provided a new explanation for the so-called "Basic Front" around many bodies of granite.

He carried out intensive investigations on the structure, petrology and geochemistry of the Singhbhum Granite, which has been proved to be a composite body with a large number of magmatic units emplaced in three distinct phases and several bodies of granitized basic metamorphics, as well as relics of still older granites (about 3800 Ma old). This discovery of the oldest crust so far known in India and in the entire eastern hemisphere was hailed as a major contribution to our knowledge of the early evolution of the earth's crust. For the first time in India, the detailed history of emplacement of a large batholithic body of granite as well as stages of the early crustal evolution has been deciphered.

In collaboration with S N Sarkar, Saha made a thorough revision of the Precambrian stratigraphy, tectonics and geochronology of Singhbhum region. As a result this region is now considered to be a model area of the Indian shield

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where the detailed geological history of a vast span of time ranging from 3800 to 900 Ma has been worked out.

Saha carried out a systematic study of the mineralogy, geochemistry and history of crystallization of some pegmatites of Bihar Mica Belt. He put forward a hypothesis based on the role of fluid pressure during crystallization of pegmatites for the genesis of muscovite books. He indicated several simple geochemical criteria for the identification of muscovite-bearing pegmatites; these criteria are now being widely used by the Geological Survey of India and other agencies in prospecting for muscovite.

In recent years, Saha has initiated research on the problems of the environment in India. Baseline studies on air quality carried out under his guidance in parts of southern Bengal have yielded valuable information on the nature and magnitude of air pollution, particularly over the rural area. The natural processes determining the distribution and migration of the pollutants have been identified and assessed through the use of techniques of factor analysis. Ingenious use of multivariate statistical techniques in the analysis of water pollution parameters has helped evolve an optimum plan for water pollution monitoring of the Ganga. Together with A B Biswas, he has demonstrated the beginning of land subsidence in parts of Calcutta, caused by continued subsidence of piezometric surface of the confined groundwater.

Saha pioneered in India the geological application of statistical techniques, including the use of trend surface analysis as well as the multivariate techniques of discrimination analysis, multiple regression modelling, cluster analysis and factor analysis to throw new light on the various processes involved in the genesis of granitic rocks; he also developed the new technique of grid deviation maps—a variant of the moving average analysis. He has put forward an ingenious hypothesis on the use of areal composition variation patterns of granite bodies for assessing their mineralization potentiality, particularly for the search of the cogenetic china clay deposits within the Singhbhum Granite. He has made pioneering contributions to the use of geomathematical technique for (i) indicating new ore shoots in the Champion Lode of Kolar Gold Field, and (ii) identification of the phases of mineralization in the Singhbhum Copper Belt.

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Ashok Sahni

Sahni has made valuable contributions to Indian geology, particularly in the fields of vertebrate palaeontology, biostratigraphy and palaeobiogeography. He has undertaken multidisciplinary research projects, which have resulted in the better understanding of specific problems, for example Karewa (Kashmir) palaeoclimates and biostratigraphy and the dating of the Deccan basalt sedimentary-intercalated sequences. Also, he has been largely instrumental in the initiation of biomineralization studies in India involving the application of electron microscopy in understanding the evolution and development of calcified tissues such as dental enamel and eggshell ultrastructure. In 1992, he was invited to convene a symposium on Fossil Hard Tissues at the 29th International Geological Congress at Kyoto, Japan.

Campanian microvertebrates from the Judith River formation, Montana

Sahni worked on Campanian microvertebrate assemblages for his Doctoral Dissertation at the Institute of Technology at the University of Minnesota, Minneapolis (1968) and established the presence of a diverse Late Cretaceous primitive mammalian fauna including one of the earliest records of marsupials. This work helped to establish a biochronology for several fossil vertebrate groups. He reported the occurrence of a variety of eggshell fragments of dinosaurs constituting the earliest report from the North American Campanian. The thesis was published[1] as a Bulletin of the American Museum of Natural History, New York (1972) and is regarded as a pioneering study of Late Cretaceous microvertebrates.

Eocene mammals from the Kashmir Himalaya and dating the India-Asia collision

In the early 1970's, when Sahni undertook the problem dealing with the India-Asia collision, there was widespread skepticism in India regarding the validity of

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plate tectonics. Using Eocene mammalian assemblages from the Subathu Formation of the Kashmir Himalaya, Sahni and Kumar[2] (1974) proposed that the India-Asia soft collision took place during the Middle Eocene. This hypothesis was based on the affinities of the Subathu mammals to those from Central Asia and has since been corroborated by other data from sea floor spreading and Lesser Himalayan stratigraphy.

The Subathu mammals represent one of the most diversified assemblages from South Asia and in fact, the early papers on this subject (Sahni and Khare[3], 1972, 1973) have led to a re-examination of critical sections in neighbouring countries.

Eocene marine mammals from Kutch

The reasons why certain terrestrial mammals adapted to marine conditions in the early Tertiary has always been an enigma. Sahni's work on the Eocene sequences of northern and western India and the significant discoveries made by him and his associates (Sahni and Mishra[4] 1975, Kumar and Sahni[5] 1986) of archaeocetes, sirenians and primitive proboscideans, have radically changed traditional concepts regarding the origin of several orders of mammals.

Evolution of dental enamel in mammals

Dental enamel constitutes one of the hardest biologically-produced materials known. Prior to Sahni's work in this field, there were hardly any studies that treated dental enamel at the microstructural level using scanning electron microscopy to study the evolutionary features of prismatic enamels. While on a Humboldt Fellowship at the University of Bonn, Sahni worked on the enamel ultrastructure of Late Cretaceous mammals from Montana[6] (USA). He followed this research by two major articles[7,8] in which he traced the dental enamel microstructure in several mammalian lineages. At present, he is involved in several research programmes of the Post Graduate Institute of Medical Research at Chandigarh in studying the effects of fluorine and carious lesions in dental enamel.

Dinosaur eggshell ultrastructure

Dinosaurian remains at Jabalpur were first reported in 1828 and represent the earliest record from Asia. Recently, Sahni has established that the dinosaurian nesting sites in India (including the ones he reported from Jabalpur) are one of the most extensive recorded globally[9]. As a sequel to his earlier study on dinosaurian eggshells from the Campanian of Montana, Sahni worked on Indian dinosaur eggshell ultrastructure and established five morphostructural types[10]. He also

extended these ultrastructural studies to examine eggshell fragments of Indian Pleistocene ostriches and a variety of eggshells of fossil lizards and crocodiles.

Reconstruction of Siwalik palaeoenvironments and communities based on microvertebrates

Microvertebrate palaeontology involving bulk maceration, screening and washing of sediments for the recovery of vertebrate microfossils was initially carried out by Sahni and Khare[11]. This technique has since been applied to various other Indian Cretaceous, Tertiary and Quaternary sequences. In the Siwaliks, the applications of the screening methods resulted in the finding of several new micromammals and lower vertebrates. Based on microvertebrates, fossil communities were characterised and differentiated.

Volcano-sedimentary sequences from the Deccan basalts: Microfossils and dating

The age of the Deccan basalts is crucial in understanding several geodynamic aspects of the Indian Plate and its movement after the break up of Gondwanaland. In the early 1980's Sahni re-examined the volcano-sedimentary sequences at Nagpur, Jabalpur and other places and worked out their microfossil content using bulk screening methods. In addition, he teamed with French scientists from Paris and Montpellier, using magnetostratigraphy and Ar/Ar dating of the flows delimiting vertebrate-bearing horizons, to demonstrate a much shorter time span for the eruption of the Deccan basalts[12]. This work later culminated in Sahni's involvement in three International Geological Correlation Programme (IGCCP 216, 245 and 350) and the publication of a Seminar proceeding[13].

Precursor basins to the Siwaliks

While many geologists have devoted their attention to the Siwalik beds, little consideration has been given to several Oligocene-Early Neogene basins which developed before the Siwaliks. These include Murree (Kashmir), Dharamashala and Kasauli Formations (Himachal Pradesh) and the Kargil and Nyoma localities near Ladakh. The occurrence of the freshwater Oligocene sediments with a diagnostic fauna has been reported from the Kargil molasse group at Ladakh[14] and represents the first record of Oligocene terrestrial mammals of Eurasiatic affinity.

Karewa vertebrate biostratigraphy

The establishment of a rodent-based stratigraphy for the Karewa sequences in the Kashmir valley has been a major gain for Sahni and his associates[15]. Prior to his involvement in the Karewa Palaeoclimate Project, micromammals were virtually

unknown in Karewa sediments. In conjunction with B S Kotlia, Sahni established the presence of climate-controlled migrations of arvicolid rodents from Eurasia during the late 3 million years.

Geochemistry and petrography of vertebrate fossils

Vertebrates are composed of hydroxyapatite and during the fossilization process, their skeletal elements may be anomalously depleted or enriched in radioactive elements. Sahni and co-workers undertook the study of uranium distribution in Siwalik and other fossil bones using fission track techniques. The preferential enrichment of uranium in vertebrate fossils has been used to trace diagenetic alterations, for taphonomic reconstruction and for the prospection of uranium deposits in non-marine sediments.

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Samarendra Nath Sarkar

Sarkar has carried out outstanding and highly significant research work on the following topics during last 4 decades: stratigraphy, tectonics, petromineralogy, geochemistry and geochronology of the Precambrians of Bhandara-Durg-Balaghat District, central India over an area of 3000 sq km.

Thorough revision of the Precambrian stratigraphy, tectonics and geochronology of Singhbhum-Keonjhar-Bonai Mayurbhanj Sundargarh and southern region of the Singhbhum-Orissa Iron Ore Craton over an area of 40,000 sq km in collaboration with Indian and foreign geoscientists. Establishment of three main crogenic cycles closing at 3800 Ma, 3000 Ma, 900 Ma and discovery of the oldest rocks in this part of the globe and possible presence of older granitic crust about 4 billion years old.

Systematic tectonic analysis in all scales and stratigraphy of the following: (i) Crystalline nappe zone in the Garhwal and Kumaon Himalayas in Nainital, Ranikhet, Almora, Lansdowne and Baijnat areas, (ii) Precambrian Sausar group rocks with manganese ore deposits of Chiklá-Dongrihizarg-Alensar-Tirodi areas, (iii) Precambrians of Ghatsila-Galudih-Mosaboni-Rakha Mines; Chakradharpur-Chaibasa, areas (iv) Noamundi-Gua-Bolani-Joda areas with bounded iron ores with ore geochemistry work on critical areas.

Precambrian geochronology of critical regions in Peninsular India and establishment of revised draw—and lithostratigraphic classification and correlation of critical regions. Seven-~~fold~~ subdivisions have been established with time limit 3800, 3500, 3000, 2500, 1600, 900 and 570 Ma in the precambrians and compared with those of the other continents. Maximum amount of pioneering top quality authoritative work has been done in India by Sarkar in this field (since 1960 till present day) as India's representative in the Precambrian subcommission of the IUGS.

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Detailed geological and ore geochemical and structural control on sulphide ore bodies and wall rocks in Mosaboni-Rakha Mines sections of the copper Belt thrust zone.

In Nagpur-Bhandara-Durg districts of Central India, geotectonically the most critical region is the triangular area of the steeply plunging Sakoli Synclinnorium (cross folded) bordered (a) on the east by the NNE trending Dongargarh belt, (b) on the NW by the ENE trending, arcuate Sausar orogenic belt.

Intensive and systematic stratigraphic, tectonic and geochronology work carried out on the Archean and Proterozoic rocks of this Supergroup over 1500 sq km area and reconnaissance survey in adjacent areas over another 1500 sq km lead to the following conclusions:

A new sequence of rocks named as Dongargarh Supergroup. These rocks constitute a belt up to about 90 km wide stretching NNE for more than 150 km between the Sakoli synclinorium on the west and Chattisgarh basin on the east. The generalised chronostratigraphic succession as determined by further work supported by relevant age data by coworkers has been established.

The oldest rock (Amgaon Group > 2500 Ma) occurs as remnants within granite gneisses and granites, and as inliers within the rocks of the Nandgaon and Khairagarh Groups and are pre-Sakoli age (forming the basement of the synclinorium) and appear to be partly granised psammopelitic metamorphics and amphibolities. Bijli rhyolites comprise about 4500m, thick formation of leuco-rhyolite with intertrappean rhyolitic conglomerate, ignimbrites, rhyolitic sandstones, siltstones, shales and tuffs. Bijli rhyolites are definitely post-Amgaon in age (2200 Na-2503 Ma old) and also post-Sakoli, based on field evidence. The Bijli rhyolites have been folded during Nandgaon orogenic phase and followed by extrusion of Pitepani volcanics. Highly folded rhyolites with steeply dipping flow layers with intertrappeans (striking N-NNE) are traceable at intervals for about 65 km across the strike and for more than 110 km along the strike between Chattisgarh basin and long 80 E. The Dongargarh granite comprising porphyritic microgranite, granophyre, prophyritic coarse grained granites, covering several thousand sq km formed after the close of Nandgaon orogenic phase (2200-2 Ma), developed a thermal aureole up to 1.6 km wide. Khairagarh Group including from bottom upwards Basal Shale (1534 Ma), Bortalao Formation intertrappean shale (1686 Ma), Sitagota Volcanics (1367 Ma), Karutola Formation, Mangikhuta Volcanics (total thickness 5455 Ma). Khairagarh orogenic phase (*c*. 900 Ma) folded the group in open folds and culminations and depressions. Over an

unconformity Chattisgarh Basins (< 900 Ma) is deposited. Three Rb-Sr WR-mineral ages of Dongargarh granites (1450-1480 Ma) and 3 Amgaon gneiss WR-Biotite ages (1460-1640 Ma) are comparable to K-Ar ages of biotite and K-feldspar (1412-1510 Ma) from granite, biotite (1300-1420 Ma) and hornblendes (1560-1662 Ma) from Amgaon gneiss indicate a period of pronounced thermal events causing reequilibration of the isotopic systems in these minerals.

For the first time four different types of S-planes and eight different types of lineations have been recognised mapped in this area. Three orogenic cycles have been recognised e.g. Amgaon, Nandgaon and Khairagarh cycles. Nine major folds from Khursipar syncline to Sahaspur syncline from W to E with cross folds, 12 major oblique slip diagonal faults including two block faults are recognised and mapped, largest being Great Darekasa fault with 9 km horizontal slip and 3.5 km dip slip component and runs for 20 km or more along N-S direction. Horizontal separation of the base of Karutola Formation is 18.5 km (sinistral). This fault extends > 150 km S-wards.

In the overlying Khairagarh Group, both the volcanic units (viz. Sitagota (1367 Ma) and younger Mangikhuta volcanics) are having very much similar major element geochemistry. This coupled with the fact that Mangikhuta and Sitagota volcanics are closely associated in the field, implies sequential event of formation and evolution of these volcanics via same/similar magma tectonic process.

With the aforesaid observations in purview, a number of petrochemical models (major element based) involving all possible source rocks/magmas and differentiation processes have been tested using a quadratic mixing programme. The salient results on the basis of 72 samples analysed are summarised below :

(a) Bijli rhyolite and Dongargarh granite can be derived from extensive partial fusion (60 to 68% respectively) of the Amgaon granitoid gneissic basement. But such partial fusion process cannot be continuous one, but was punctuated by the Pitepani basic volcanism.

(b) The pitepani volcanics characterised by very high K 20% (mean = 2.36%) could not be generated from a mantle derived melt of primitive (picritic) character. Their main possible source would be the amphibolites (ortho) of Amgaon Group—which on extensive partial melting might have generated a parental melt—which in turn received possible contributions from the Bijli rhyolitic rock and/or K-

feldspars from Amgaon granitoid gneiss to generate the Pitepani basic volcanics.

(c) Both Sitagota and Mangikhuta volcanics can be modelled to be generated by extensive fractional crystallisation (C.55%) of clivine (Fo-80), plagioclase, clinopyroxenes $\pm$ spinel and ilmenite from a picritic parental magma. Both Sitagota and Mangikhuta (LKT) basalts have continental—oceanic (island/rift ridge) affinity. Similar observations are also recorded by a number of workers, who consider such lithologic sequences as representative of continental rifting and related subsidence—which on further separation caused attenuation of the crust by partial fusion in the early stage when the acid and basic magnetism of Nandgaon group (all crustal derived) took place. On continued separation, the crust was ruptured and direct contribution from the mantle was initiated—perhaps in the form of quantised generation mantle partial melts (of picritic character) which, in turn through extensive fractionation evolved to the Sitagota and Mangikhuta basalts.

Multiple methods of dating have been used on three suites of rocks of the Singhbhum region, East India. Samples of older Metamorphic Tonalite Gneiss (OMTG) and MGO yield the following results: Sm-Nd Wr isochron ages (3.775 Ma) indicates the time of crystallisation of OMTG, which is supported by WR Pb-Pb isochron age (3.66 Ga) of Champua samples. ^{40}Ar-^{30}Ar dating indicates deformation and regional metamorphism of OMG and OMTG during 3.3 to 3.5 Ga, Pb-Sr WR isochron ages (3.1-3.2 Ga) and K-Ar mineral dates (3.07-3.32 Ga) mark later thermal events affecting OMG and OMTG.

In case of Singhbhum Granite samples Pb-Pb WR isochron age (3.297 G) and ^{40}Ar-^{39}Ar age (3.3 Ga) indicate the age of crystallisation of SG-Phase II. Rb-Sr WR ages (2.89-3.05 Ga) and K-Ar biotite ages (2.65-2.71 Ga) suggest youngest thermal event affecting WR and certain minerals. WR Pb-Pb age (3.07 Ga) and WR Sm-Nd age (3.12 Ga) indicate that the SG-Phase III crystallised around 3.1 Ga.

In case of Soda granites from Singhbhum shear zone, Pb-Pb WR accurate isochron age (2.2 Ga) marks the time of crystallisation, and Rb-Sr WR isochron (1.63-1.65 Ga) mark the age of deformation and retrogressive metamorphism. The analysed Soda granite (12 samples) belong to a suite of leucocratic schistose granites from shear zone. They have an unusual composition with Na_2O/K_2O ranging from 0.68 + 17.8 and with $Na_2O + K_2O$ in the range of 4.7%, which is

low for silicic igneous rocks. They are also low in CaO (av. 1.42%). Their Pb and Sr contents reflect the major element chemistry, Rb being 12-70 ppm and Sr 32 + 21 ppm averaging 38 ppm and 52 ppm, respectively.

The early history of the Singhbhum-Orissa Iron ore Craton in East India covering a period from c.4.0 to c.3.0 Ga has been deciphered in some detail through interpretation of the results of structural, stratigraphic, geochronolic and geochemical studies in parts of the region. The cratonic block is bounded by the arcuate Copper Belt thrust zone on the north and Sukinda thrust zone in the south and is essentially a Greenstone-Granite province with relics of early Archean amphibolite facies rocks, while the Satpura Belt rocks to the east and north are generally amphibolite facies and the Eastern Ghat Belt rocks lying to the south belong to Granulite facies.

The patterns of early crustal development of the craton differs in several ways from that in other known early Archean terrains in Greenland, South Africa and South India; viz. (a) indication of sial formation event prior to 3.8 Ga; (b) existence of 3.8 Ga old supracrustals with strong resemblance to phenerozoic supracrustals; (c) rarity of ultramafics and rocks of Komatüitic affinity; (d) rapid thickening of the continental crust to at least 30 km by 3.8 Ga. A model of crustal development starting with formation of a sink zone in the then ultramafic/mafic crust at c.4.0 Ga through successive accretion of mafic and salic materials derived from upper mantle as well as by metamorphism of the supracrustals explains the observed data satisfactorily. The major crust forming events in this craton were practically complete by 3.0 Ga.

^{40}Ar-^{39}Ar incremental heating studies on mineral separates from three sets of rocks in the Singhbhum craton in eastern India have helped unravel the thermo-chronometric history of the terrane and explain an earlier discrepancy between Sm-Nd (c. 3800 Ma) and Pb-Sr (c. 3100 Ma) whole rock ages for the older Metamorphic Tonalitic Gneiss (OMTG). High precision plateau ages for hornblende separates from the older metamorphic group of rocks (OMG), suggesting that this unit is older than 3300 Ma and that enclaves of both the OMTG and OMG within the batholithic complex cooled to c. 500°C at 3300 $\pm$ Ma following engulfment in magma, forming the Singhbhum Granite (SG). Results from a biotite separate from the OMTG imply that slow cooling continued to a temperature of -300°C at c. 3160 Ma. Study of a feldspar separate from the Singhbum Granite, suggests final cooling (uplift) through the c 150°C isotherm c. 660 Ma ago.

Sarkar and coworkers suggest that an earlier Rb-Sr whole rockage of 3130 ± 85 Ma ago on the OMTG did not yield the crystallisation age, but rather the time of cooling to Sr retention temperature for the biotite in these rocks. They also demonstrate that for hornblende and mica from Archean, rocks ^{40}Ar-^{39}Ar incremental heating experiment can yield very high precision plateau ages (e.g., ± 2 to ± 5 Ma to 3300 Ma). In practice however they suggest this technique can separate events in the early Archean spaced c. 30 Ma apart.

Geochemical data including rare earth element (REE) and large-ion lithophile element (LILE) concentrations in the early Archean amphibolites of the Singhbhum-Orissa Iron Ore Craton are reported. Considering the tectonic setting along with results of major and trace element and REE-modelling it appears that (a) the older Metamorphic group (OMG) orthoamphibolites (> 3775 Ga) probably evolved through two stages—(a) partial fusion (c 11%) of a LIL-enriched pyrolitic mantle material to generate an olivine tholeitic primary melt followed by (b) fractional crystallisation (c. 55%)- of olivine, plagioclase, and clinopyroxene at shallow level. (c) The OMG para-amphibolite is the product of weathering of LKT-type mafic rocks and shows relatively higher and variable concentration of REE enriched mineral components.

Polycyclic metamorphic history in the multiple deformed eastern part of the North Singhbhum Mobile Belt reveal the presence of a pronounced early pre-tectonic metamorphic cycle: MO characterised by development of andalusite, chloritoid, diotite, some garnet and perhaps some kyanite. While the M1 metamorphic cycle, coeval with F_1-D_1, fold deformation phase is marked by crystallisation of syn-to post tectonic biotite, garnet, staurolite, Kyanite and rare chloritoid, attainment of major metamorphic peak is denoted during M_2 cycle with formation of significant proportion of syn to late tectonic Kyanite staurolite and some biotite related to F_2-D_2 phase. Various metamorphic reactions based on the crit cal examination of prevailing mineral assemblages and paragenesis suggest .he metamorphites to be a product of low-to-medium press between 3-6 kb and 415-600°C. The metamorphism is by and large progressive in time and space.

A model of crustal distension, upwelling of mantle plume, migration of volcanic exhalatives and hyrotherms is envisaged to provide a high enough *dp*/*dT* to produce a dominant early pretectonic MO cycle of metamorphism through the role of strain heating cannot be overlooked during M_1 and M_2 cycles.

Aerial photo interpretation of the Precambrian terrain of Pala Lahara-Kulanga, covering parts of toposheets 73 G/3, G/7, and G/8, was carried out on

1:60,000 scale. This, as well as remote sensing studies on regional scale on Landsat TM imagery (1:250,000) and Band 7 imagery (1:1,000,000), supported by ground check in critical areas, reveal the presence of a complex twisted T-shaped Malayagiri syncline and Sikheswar-Sundarmundi syncline, which include a psammitic to semi-psammitic rock sequence with Banded Iron Formation (Pala Lahara Group). Minute details of superposed folding of three generations are recognisable within the Pala Lahara Group.

Structural studies indicate first two stages of folding along NNW-SSE axial trace followed by a third stage of cross-folding along E-W to ESE-WNW axial trace, mainly controlled by basement configurations in the west and east domains, respectively. Magnetite-rich grey granite gneisses affected by all the folding phases in the Pala Lahara Group constitute the basement.

The NNW-SSE Dhinkeswar fault affecting the eastern part of the synclines runs up to 50 km. In the north, south-dipping Mankarhachua Group (sandstone, conglomerates, etc.) ends against an E-W fault zone marked by sheared schistose quartzite.

Photo-interpretation (aerial photographs and TM imageries) of the Bonai Granitic Complex and the associated supracrustals in Sundargarh District, Orissa, combined with ground check and mapping in critical areas, reveal that the Bonai Granitic Complex is made up of two units. The earlier unit (I) is tonalitic migmatite with small amphibolite enclaves and the latter unit (II) is porphyritic Bonai Granite, which intrudes the tonalite and the basal iron ore group quartzites and lavas. The IOG quartzites and lavas appear to have been deposited on the earlier unit (I) (ground data) and then folded asymmetrically. This was followed by emplacement of the porphyritic Bonai Granite (II) at the core of a doubly plunging anticlinorium.

The studies further reveal the presence of a major southward plunging open synclinal structure defined by a greenish quartzite enclave in the Bonai Granite. This structural trend is oblique to the overall north-easterly strike of the quartzites bordering the Bonai Granite. To the west and north-west of the Bonai Granite a rudaceous-arenaceous sequence, younging towards north-west, unconformably overlies the Bonai Granite and IOG supracrustals. This sequence forms an open syncline plunging northward with north-south axial trace. This rudaceous-araneceous sequence may be correlated with the lower part of the Birtola Formation of Darjing Group.

Correspondence analysis of two multi-element data sets from Sargipalli lead-zinc and Mosaboni copper mines situated within the Gangpur-Singhbhum metallo-tectonic belt is attempted to correlate between anomalouus sites associated with high metal concentrations in specific metal elements copper, lead and zinc, with a view to shed light on the metallo-genesis. The analysis identifies a close genetic link between copper, lead and zinc which have their highest concentration in the ore bearing greisen/quartz-chlorite schist occurring within, and grade into, granite pegmatite/soda granite. The gradual and systematic trace element variation in time and space within and between the data sets considered seems to reflect overall trends of evolution of parent ore bearing fluids, from which Mosaboni copper and Sargipally lead were successively derived.

The structural history of a part of the folded Baijnath nappe superposed on the inner sedimentary belt in the Baijnath-Kausani-Someshwar area in Almora district, UP has been studied. Three types of S-planes and four types of linear structures have been recognised in the area. S_1 (stratification layer) and S_2 (axial plane foliation) are parallel to each other except near the first fold (b_1) closures. S_3-crenulation cleavage is parallel to the axial plane of puckered S_2. The linear structures include L_1-rare minor first folds on S_1; L_2-groove and mineral lineation on S_2, parallel to the *a* direction of tectonic transport; L_3-older puckers of *a* type on S_2 subparallel or oblique (up to 35° to L_2); L_4-later puckers subnormal to L_2 and L_3. Three different phases of deformation, viz. F_1, F_2 and F_3 have been recognised both in the crystalline zone and inner sedimentary rocks. During the first phase of deformation F_1, minor asymmetric to isoclinal recumbent type first folds (B_1) with broadly synchronous axial plane foliation S_2, were formed. During the second phase of deformation F_2, mineral and groove lineation L_2 and older puckers L_3 were formed on S_2 at the first stage, and younger puckers L_4 and crenulation cleavage S_3 were formed during the second stage. The groove and mineral lineations L_2 were developed by intense interplanner slip parallel to *a* direction of tectonic transport from NE to SW. Older puckers L_3 oblique to L_2, were formed by convergent movement along *a*, with slight change in movement plane. The younger puckers L_4 on S_2, subnormal to the direction of tectonic transport, and making 60°-90° with L_2 or L_3 were developed due to slight change in movement pattern. Crenulation cleavage S_3 was developed with progressive deformation along the attenuated limbs of L_4 puckers by a combination of flexure slip and shearing phenomena. In the crystalline zone rocks, during the third phase F_3, all the earlier fabric elements were folded into a form of a macroscopic synformal structure approaching a conical form having a subvertical cone axis, associated with mesoscopic folds with variable axial traces. In the case of the

inner sedimentary rocks the earlier fabric elements were folded into the form of a macroscopic synclinal structure (SN-1) approaching a conical form. Symmetry with respect to all the fabric element is triclime in moroscopic and microscopic scales/representing B_1^B_2^B_3 tectonites, developed by three phases of deformation F_1, F_2 and F_3 during Himalayan orogenic cycle.

Systematic analysis of structural geometry of a part of the Sausar Group rocks in Chila-Sitekesa area throws new light on the tectonic pattern and evolution of the area. The country rocks mainly include Tirodi gneiss, Sitasaongi, Lohangi, Mansar, Chorbaoli and Junewani formations and three ore-horizons of the Sausar Group in which four types of *s*-planes (S_1-S_4) and six types of linear structures (L_1-L_6) have been recognised.

Tectonic analysis indicates that the rocks of the area exhibit triclinic symmetry in megascopic, mesoscopic and macroscopic scale with reference to all structural elements, though there are domains of monoclinic symmetry with reference to one or more fabric elements.

Kinematic analysis indicates the generation of isoclinal (B_1) folds and rootless hinges with axial planes mostly dipping SSE due to rotational stress (P_1) along N168°-N348° with anticlockwise rotation sense when looking ENE. Considerable variation in the orientation of the first-fold axes may be due to inhomogeneity of rock pile, irregular distribution of stresses and different degrees and phases of deformation. Subhorizontal stress (P_2) acting along N10°-N190° with deformation plane dipping steeply westward is responsible for the generation of east to south-east plunging L_5 puckers and minor (B_2) folds along with steeply dipping S_3 planes on S_2. Stress (P_3) acting along N146°-N326° seems to have generated widely spaced kink bands and gentle superimposed L_6 folds on S_2 in Sector-I and Sector-III and macroscopic scale antiformal B_3 fold (Alesur antiform) in Sector-II. The rocks represent B_1^B_2^B_3 tectonites formed during successive deformation phases (F_1-F_3) of the Sausar orogenic cycle.

The Singhbhum-Orissa Iron Ore craton which is bounded by the Copper Belt Thrust in the north and the Sukinda Thrust in the South represents one of the continental nuclei of the Indian Shield. An unusually long succession of crust-forming geological events ranging from well before 3.8 byr to 0.85 byr are represented in this craton. A pervading system of N 30°E-trending photolinears, as revealed in the Landsat satellite imagery characterizes this craton.

The oldest recognisable orogenic cycle is represented by the Older Metamorphic cycle (Ca. 3800-3200 Ma), during which the Older Metamorphic

para-and ortho-metamorphic rocks along with the intrusive biotite (hornblende) tonalite-gneiss-trondhjemite were folded in two stages. This was followed by the deposition of the Iron Ore Group sediments and eruption of salic-mafic volcanics which were also folded in two to three stages; emplacement of the late-kinematic composite batholithic body of the Singhbhum Granite (ca. 2950 Ma) marked the end of the Iron Ore Orogenic cycle. Emplacement of two other batholithic bodies, viz. the Nilgiri Granite and the Bonai Granite were possibly synchronous with that of the Singhbhum Granite. Widespread sedimentation, metamorphism and igneous activity occurred in the north-eastern part of the craton around ca. 2300-2000 Ma. Here deposition and metamorphism of the pelitic and arenaceous sediments of the Chaibasa Formation were succeeded by deposition of a thick sequence of arenaceous sediments and mafic lavas (Dhanjori Group) in two large marine basins; this was followed by emplacement of ultramafics, gabbro-anorthosite and then the alkali-rich composite Mayurbhanj Granite batholith. Probably during the same general period, widespread mafic volcanism (Jagannathpur Lava, Matangtoli Lava) and sedimentation (Kolhan Group) occurred in one or several marine basins to the west of the Singhbum Granite batholith. Intra-plate subduction along the northern edge of the craton (Copper Belt Thrust Zone) probably commenced around 2300 Ma; this subduction appears to have continued intermittently till about 850 Ma.

Six whole rock samples of the Tirodi gneiss belonging to the basal part of the Sausar Group rocks in the Dongri Buzurg area yield a good Rb-Sr isochron corresponding to an age of 1525 $\pm$ 70 Ma and an initial Sr ratio of 0.7148 $\pm$ 0.0033. Mineral isochrons for two of these rocks give concordant but younger ages at 860 Ma, in good agreement with the previously reported K/Ar ages on minerals separated from the Sausar Group rocks. The 1525 Ma event is interpreted to mark the main phase of regional metamorphism of the Sausar Group of rocks including the granitization of the basal Tirodi unit. the deposition of the sediments of the Sausar Group and their basement must therefore be even older. The good agreement of the Rb/Sr and K/Ar mineral ages at about 860 Ma indicates the latest thermal overprint on the sausar rocks. The regional metamorphism of the Tirodi gneiss at about 1500 Ma ago is also reflected in the Rb/Sr and K/Ar mineral ages of the Amgaon gneiss and Dongargarh granite to the east of the Tirodi gneiss.

On the basis of geochemical profiles (semi-log plots) and other diagrams (log-log plots) prepared from several thousand multi-element analytical data on the samples of wall rocks and ores systematically collected across the ore bodies

in different levels of the Mosaboni (CS, NB and NS) and Rakha Mines for the first time, to study the variation pattern across the ore zones and down the depth the following generalizations have been made.

(1) In the geochemical profiles, Ni, Co, Pb and Zn usually show sympathetic variation with the Cu content across the ore zone. Sometimes (Co + Ni)/(Pb + Zn) ratio also shows similar variations. The trace elements show log-normal distribution.

(2) The wall rocks are usually rich in Ni and Co.

(3) The Ag content is usually independent of Cu content and may be present either in wall rock or ore in different amounts (0.25030 ppm or more).

(4) Ni/Co ratio in wall rocks and ore zones usually varied between 1 and 10 and Ni:Co plots show overlapping fields within certain limits for different levels and mine sections. The average Ni/Co ratio shows fluctuating values and a general increase downwards in most cases, e.g. (Co + Ni)/(Pb + Zn) ratio in wall rocks and ores usually varies between 1 and 10 and sometimes below 1; and above 10 (in ores). The (Co + Ni): (Pb + Zn) plots show overlapping fields within certain limits in different levels and mine sections, and average ratio shows fluctuating values with a tendency to generally increase downwards.

A multivariate statistical analysis was carried out with the log-transformed values of Cu, Ni, Co, Pb, Zn, Ag, Cr, Mn, Ca and Sr in several sets of samples collected across the ore bodies in the Central Section, Mosaboni Mines, Linear correlation coefficient matrices of two sets of ore samples (0.5% Cu), one from levels 18 and 21 and the other from levels 25 and 28 indicate two well defined and distinct clusters comprising of Cu, Ni, Co, Pb, Zn on the one hand Ca, Sr, Mn on the other.

Varimax-rotated R-mode Factor analysis of two above noted sample sets, taken along with the available geological information, indicate that over 88% of the variability in data matrices for 9-10 elements can be accounted for by four distinct processes:

(a) an early phase of copper- mineralisation which apparently replaced Mn, Ca and Sr in the host rock;

(b) silicate-cum-oxide phase of crystallisation/recrystallisation of the host rocks;

(c) remobilisation of the sulphide-forming ore elements (Cu Ni, Co, Pb and Zn); and

(d) a phase of mineralisation of Ag which appears to have replaced Cr, Ca and Cu, the process (c) was quantitatively the most important. Factor score studies are suggestive of preferred introduction of Ni, Co, Pb and Zn along the central parts of the proexisting copper-mineralised zone.

The sulphur, isotopic studies on six representative chalcopyrite samples from levels 20, 24, 25, 26, 28 and 38, Mosaboni Mines show $\delta^{34}S$ permil values : + 7.2, + 4.9, + 5.9, + 4.2, + 6.3, + 5.4 respectively and they are comparable to earlier data on 3 samples (+3.3 to +4.4) for Mosaboni and 6 samples (+3.6 to +4.6) for Roam adit.

In the present investigation Sarkar and coworkers think the source or sulphur may be magmatic hydrothermal with some amount of crustal contamination at shallow levels. Such narrow range of $\delta^{34}S$ permil values (+3.3 to +7.2) in 15 samples in the different levels of Mosaboni and Roam support the magmatic hydrothermal origin and contamination with the volcano-sedimentary pile supplying the ore elements.

On the basis of 220 EMPA data on coexisting sulphide minerals in levels 18, 21 and 25 from Central Section, Mosaboni Mines the following conclusions have been drawn:

(1) Sulphides like chalcopyrite, pyrite, pyrrhotite and other minerals showed compositional variation within certain limits from the ideal composition, within a few mm and in different levels.

(2) In Mosaboni, great variation in Co and Ni contents in coexisting pyrite and pyrrhotite support hydrothermal origin. High content of Co in pyrite and high Ni content in coexisting pyrrhotite suggest metamorphic recrystallisation.

(3) Pentlandities show high Co contents (at % 2.36 to 2.55) which is higher than various natural Pentlandities in well known samples.

(4) A new mineral siegenite with an average compositon of (Ni_{10} Co_{15} Fe_{55} S_{33})-(Ni, Co, Fe)$_{23.6-25.6}S_{32}$ is found (not reported earlier from this region).

(5) Partitioning coefficients of Ni in coexisting pyrite-pyrrhotite pairs in 18th and 22nd levels, Mosaboni indicates equillibration temperatures ranging between 250°C and 325°C, which are close to the

homogenisation temperature of 291°C-320°C in 18th and 21st levels, obtained from fluid inclusion studies on quartz samples.

(6) Very recently more elaborate and third inclusion and stable isotope studies ($\delta^{18}O$ values) on quartz samples from Mosaboni (CS, NB, NS) by another group of coordinating scientists (Changkakoti, Gray, Morton and Sarkar, 1987) reveal homogenisation temperatures for primary inclusions between 324 and 430°C for the north-section, between 275 and 410°C for the central section, and between 328 and 450°C for the south section. Salinities of the fluids were between 35.0 and 51.0 wt % NaCl equivalent. The $\delta^{18}O$ values of quartz were between 4.17 and 7.17 per mil (SMOW). The δD values of primary fluid inclusion waters extracted from quartz were between -32.7 and -39.8 permil (SMOW). The *D* values for secondary fluid inclusion waters were between -55.5 and -95.3 permil (SMOW). The calculated oxygen isotopic compositions of the fluid inclusion and stable isotope results suggest that this copper deposit originated in the deeply penetrating fault zone from saline connate waters which had a meteoric precursor, or from deeply circulating meteoric waters.

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Vasudeva Vavilala Sastri

Sastri is one of those scientists, who believe that science has to serve the society and the country and the benefits of research have to be felt by the common man in his urge to raise his standard of living for a better life. His researches had an impact towards that objective. Basic researches are only a means to an end.

Sastri is a pioneer in the Post Independence era in initiating the studies on microforaminifera from India, Pakistan and Burma for the Geological Survey of India, Calcutta in 1949 and its application to oil exploration in India. He started his scientific career with the erstwhile Assam Oil Co. (Now Oil India Lid.) at Digboi, Assam, way back in 1947, as a micropaleontologist. He spent all his 45 years of active service in researches directly connected with oil exploration; in micropaleontology; stratigraphy: sedimentary basin analysis and evaluation; and geotectonics of India and Asia.

Sastri led a team in the preparation of an Oil & Gas Map of Asia, on 1:5 million scale, published by the United Nations in 1975, which is an international recognition to an Indian oil explorationist. Subsequently he had prepared revised editions of the map, in 1985 and 1989, published by U N. Sastri worked as an Economic Affairs Officer during 1982-83 and as a consultant to U N for many years, on Geotectonics & Oil Exploration of Asia.

Sastri's studies on microforaminifera (1947-49) led to the establishment of a good stratigraphic correlation between Upper Assam and Surma Valley. His studies were extended to the Mesozoic Planktonics of Sind Beluchistan region (Lakra Test Well). The Jaisalmer (Rajasthan) area received his attention, which resulted in new concepts on the paleogeographic reconstruction of the region.

Formerly, General Manager and Director KDM, Institute of Petroleum Exploration, Oil & Nat Gas Commission; Economic Affairs Officer and Consultant to the United Nations; Geological Adviser PETRONAS—the Malaysian National Oil Co., Emeritus Scientists, CSIR, Jawaharlal Nehru University, New Delhi; *Residence* : EA 1/18, Inderpuri, New Delhi 110 012.

When Sastri acted as a consultant (1951-52) to the Standard Vacuum Oil Co. at Calcutta, for Oil Exploration in West Bengal, he brought out valuable information on the subsurface stratigraphy of the Bengal Basin.

Sastri extended his studies to the East Coast and Kerala Coast, which resulted in the discovery of new stratigraphic units and new Microfossil assemblages.

Sastri's geological field work in the then Madhya Bharat, along with M K Roy Chowdhery of the Geological Survey of India, resulted in a new authentic geological map and revised stratigraphy of Bagh beds, which hold good even today.

One of Sastri's classical contributions jointly with M R Sahni of the Geological Survey of India to Indian micropaleontology was contained in an exhaustive taxonomical and stratigraphy review of the Orbitolines of Burma, Tibet and India (Chitral, Gilgit and Kashmir) published by the Geological Survey of India as Memoir in 1957.

For the first time, the Sriperumbudur beds, near Madras, yielded a microfauna which indicated a parallic sequence and similarly the Raghavapuram Shales at East Coast yielded new assemblages, which led to a revision of our concepts that existed then.

Outside oil exploration, in the Energy Sector, it is significant to record that the geothermal steam Reserves of Puga Valley (Ladakh) were estimated by Sastri for generation of electricity. The geotectonics of the Valley were also studied by him in the company of V S Krishswamy, the then Director General of Geological Survey of India.

It is no exaggeration to note that the oil and natural gas would not have been produced from the Krishna-Godavari basin but for Sastri's insistence with the ONGC, to drill and test the basin's potential. Sastri concentrated his scientific studies on the stratigraphy and geotectonics of the basin for a number of years. He evolved new concepts regarding the evolution of and hydrocarbon generation in the basin. His prediction of the extension of Pranhita-Godavari graben into the Godavari delta, onland and offshore, has only come true. The postulated periodic oscillations of the graben resulted in maturation of sediments in the delta and release of hydrocarbons. The high geothermal gradient at the SE end of the exposed graben, due to the Hotspot, was studied. The Deccan Traps, the Inter-trappean sediments were studied in great details from the oil exploration point of view.

The geochemical studies carried out on the white surface encrustations over the alluvium of Krishna river Delta were found to be a direct manifestation of subsurface hydrocarbons.

The geotectonics and evolution of the Mahanadi, Godavari, Krishna, Palar and Cauvery river basins, were studied in great detail, at the Jawaharlal Nehru University, New Delhi, under a research grant from CSIR. The results of the study were made use of by ONGC and OIL. His concepts on Delta Modelling for East Coast basins have come to stay.

Sastri's studies have indicated good qualities of natural gas at shallow depths (up to 500 metres) in the Godavari-Krishna delta region, which when exploited can positively augment the energy needs of the rural fold of the area, at a low cost. His scientific surmise (1972) on the presence of Carbonates (limestones) in the Bombay High area, has come true after later drilling.

The upper mantle plume of the SE end of pranhita Godavari graben, the effect of the subsea volcanic vent on the evolution of the East Coast of India and the Bay of Bengal are some of the recent researches that are being pursued by Sastri.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Saurindra Nath Sen

Sen was the first to take up research on magmatectonics and petrofabric analysis in India. He elucidated the mechanism and effects of intrusion of a lensoid body of porphyritic granite in Manbhum, Purulia district on the basis of (1) magmatectonic features of the granite, (2) statistical study of joint distribution in the wall rocks, and (3) effects of emplacement of the granite on other megascopic and microscopic fabric of the country rocks[1-3]. This pioneering effort in India fetched Sen a DSc degree, and an offer from the Columbia University, New York, through the Fulbright-Smithmundt exchange programme, to introduce these topics in their curriculum and apply modern techniques of structural geology (as in the early fifties through the work of Sander, Cloos and Wegmann) in their research programme[4].

Sen's work on granulite and amphibolite facies metamorphic rocks in Manbhum[5], especially on some charnockitic assemblages[6,7] and calc-magnesian metasediments and amphibolites[8] has been referred to widely. His two contributions that have attracted wide attention are: (i) explanation of interlayering of calc-silicate rocks and amphibolites by metamorphic differentiation from close and gradational association of the two lithologies, and (ii) derivation of hornblende in some of the charnockitic assemblages from pyroxene, in a retrograde trend.

Sen's interest in the response of single crystals in a rock volume to changed stress environment, and their recrystallization at raised temperatures, led to a study of deformed labradorite plagioclase crystals in a banded norite from Oregon, USA. Planes of gliding were located crystallographically and verified from the structure and packing of the mineral[9].

In the field of Precambrian geology, the work on a part of the Holenarsipur schist belt of Karnataka indicated an approach towards appreciation of

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stratigraphic relations of the rocks which was different from the hitherto practised methods in the region and yielded results significantly different from those of earlier workers, except for a tectonic-cum-petrogenetic interpretation offered later from landsat imagery by Drury[10]. Sustained work on the structure, tectonics and stratigraphy of the rocks of the Aravalli Range and its environs started with a detailed investigation of the structural geometry of selected areas in the region by Sen[11] and his colleagues. Structure mapping, traverse across the Range, reconnaisance mapping in the intervening tract and study of aerial photographs have yielded a comprehensive picture of the tectonic set-up of the Range, necessitating a drastic change in the stratigraphic reconstruction and reconstruction of the structural history of the crystalline Precambrians of the region[12,15]. The most important result that has emerged from this study is the identification and mapping in the Aravalli Range of several parallel NE-SW trending independent tectonic units. The temporal relationship of these tectonic zones pictured from the structural studies has received corroborative support from geochronologic work of Gopalan and his group. The tectonic history of the Proterozoic mountain belt and the temporal and genetic relationship of the tectonic zones within the belt have been traced in the light of the plate tectonic paradigm. The identification of a Palaeosuture (a Proterozoic subduction) east of the Delhi belt and west of the belt was among the earliest such demonstrations from the Precambrian tracts[12-14].

Results of geomorphological studies through aerial photographs, morphometric analyses, selected river valley analyses and characterization of sediments of their flood plains, leading to the recognition of several geomorphological provinces, were utilized in interpreting recent movements in the Aravalli tract that was triggered off by a post-Neogene reactivation of Precambrian fault surfaces. This movement was ascribed to the stress generated on the frontal part of the Indian continental plate and, to some distance back, by the continent:continent collision involved in the closing stages of the Himalayan orogeny. A quantitative analysis, based on some basic assumptions of the rheologic behaviour of the crust and the mantle and on the known extent of differential movement, yielded reasonable results for the physical parameters of the elements participating in the process[15].

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Sisir Kumar Sen

The main questions addressed in the research work of Sen and his associates are related to chemical equilibrium in metamorphic rocks, and the response of chemical equilibria to changing PT conditions. The main tools employed for answering these questions have been the chemical characters of common rock-forming solid solutions mainly plagioclase feldspar, pyroxenes, calcic amphiboles, biotite and garnet and analysis of compositional relationships between coexisting minerals in terms of thermodynamics and crystal chemistry. Enquiries into metamorphic reactions and rock chemistry constituted a natural complement to these investigations. Among Indian workers, Sen pioneered the use of the potent tool of mineral chemistry for illuminating important issues of metamorphic petrology and geochemistry.

Antiperthites and plagioclase chemistry

The work on the chemistry of plagioclase from different environments clarified the issue of solid solubility of the K, Ba, Sr components as well as the contents of Fe and Ti. It was shown that in general solubility increased with temperature of metamorphism: this finding offered a good explanation for the near-exclusive occurrence of antiperthitic plagioclases (oligoclase to labradorite) in granulite facies rocks[1,2].

Geothermometry, geobarometry and geohygrometry

The earlier work of Sen and Chakraborty (1967) on biotite—garnet equilibria from a suite of metapelites belonging to different metamorphic grades demonstrated that when corrected for the additional Ca- and Mn- components of the relevant solid solutions, the distribution coefficients with respect to Mg and Fe^{2+} between biotite and garnet correlate with increasing temperatures of metamorphism[3]. A continuing interest in this subject resulted in the formulation and modification of several geothermometers during 1984-1992, made possible

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by the calorimetric and other experimental data on several mineral mixtures that become available during this time. An orthopyroxene-garnet Mg-Fe exchange thermometer was advanced in 1984 and was refined in 1991 on the basis of an internally consistent set of activity—composition relations constrained from calorimetric and phase equilibrium experiments[4,5]. The latter data set also helped refine the orthopyroxene-garnet-plagioclase-quartz barometer. A better version of the cordierite-garnet thermometer was formulated by adopting a symmetric regular solution model for the mixing of Fe and Mg in cordierite in combination with updated values of mixing parameter of the Fe-, Mg-, Ca- and Mn- end members in garnet[6]. For the biotite-garnet thermometer which has several formulations, a thermodynamic model that explains the discrepancies between the two sets of experimentally derived Fe-Mg Partitioning data of Ferry and Spear and Perchuk and Lavrenteva was advanced.

In the field of geobarometry, a geobarometer based on the equilibrium garnet + clinopyroxene + quartz = 2 orthopyroxene + anorthite was advanced : it has the advantage that the equilibrium constant contains only one activity term for the garnet solid solutions.

An analysis of the energetics of hydration of cordierite yielded Gibbs free energy and volume changes attendant upon hydration of magnesian cordierites—this was extracted from the published high pressure experimental data at $P_{H_2O} = P_{total}$. Based on these and related thermochemical data, a method of computing H_2O in cordierites and $P_{H_2O} < P_{total}$ was devised and tested successfully[7].

These P, T and P_{H2O} sensors are currently being used by international workers.

Petrology and geochemistry of granulites

Much of Sen's research, whether related to general petrological tool or specific petrological-geochemical issues, concerns high grade granulite metamorphism and its products.

Investigations on basic (or mafic) granulites brought to light several features which were not known before and which improves our understanding of the evolution of these widespread rocks:

(a) The breakdown of common hornblende under granulite facies conditions is dependent on the activity[8] of silica as well as of H_2O.

(b) In areas such as the type charnockite area near Madras, the pyroxene granulites are chemically modified versions of hornblende-pyroxene granulites[9].

(c) Hornblende acts as a buffer in orthopyroxene-clinopyroxene equilibria and its Al contents affect the Mg-Fe partitioning coefficients between the pyroxenes,

(d) There is no compositional variance, with respect to Fe and Mg, in the hornblende-orthopyroxene-clinipyroxene subsystem of basic granulites, and the match between the Mg/(Mg + Fe) ratios of parent rocks and their hornblendes indicates a primary or prograde origin for the major variety of green-brown hornblendes in basic granulites[10]. This relation was shown to be valid for basic granulites the world over. Such hornblendes were believed to be secondary or retrograde by many workers; secondly, the prograde nature implies hornblende-bearing precursors for basic granulites.

(e) A comparative geochemical analysis of mafic granulites from three Indian Precambrian terranes and several greenstone metaborsites underscored their similarity—this permits evolution of granulite terranes through greenstone stages or as coeval roots of greenstone belts. Further, it was shown that tholeiitic trends are quite common in basic granulites, that there are significant chemical differences between Precambrian and recent basalts, and that there is a suggestion of komatiitic affinity in some basic granulites.

(f) Garnet-bearing basic granulites occur in many areas, and it was demonstrated on the basis of mineral chemistry, metamorphic reactions and phase equilibria that garnets originated by near-isobaric cooling in a suite of basic granulites from Saltora, West Bengal[11,12]. It is noteworthy that a recent sophisticated analysis of the P-T-t path traversed by these rocks has upheld the conclusion.

The P-T-f_{H_2O}-f_{O_2} regimes during the evolution of quartzofeldspathic and metapelitic granulites from several areas were analysed and the following relations, of general significance, were uncovered.

The a_{H_2O} values in the Madras granulites were locally buffered by mineral equilibria and lowered by dehydration melting. Partial melts participated in the configuration of the total chemical equilibria and were responsible for lower a_{H_2O} values in the metapelites as compared to the quartzofeldspathic granulites (charnockites)[13]. The presence of a_{H_2O} gradients argues against control of fluid

fugacities through pervasive influx of CO_2, as is believed by some petrologists. An external control of fluid fugacities is however suggested by near-uniform a_{H_2O} values in these two groups of rocks as at Satnuru, Karnataka, but this is not a sufficient condition to invoke[14] influx of CO_2. Related to these conclusions are the findings on a set of iron formations from Satnuru that f_{O_2} values were buffered in these rocks.

During the past three years, a suite of Proterozoic granulites around the Chilka Lake, Orissa are being investigated. In addition to interesting findings such as the presence of isothermal decompression sectors in the P-T-t paths traversed by the Chilka granulites, a case has been made, on structural grounds, that patchy charnockites (the so-called incipient charnockites) represent remnants rather than new growths through leptynite-charnockite transformation[15]. Data on rock chemistry and mineral reactions are compatible with this interpretation. Examination of similar occurrences in some other areas shows that the Chilka scenario may not be unique and we may have to reexamine the presiding hypotheses of origin of such charnockites by later influx of CO_2-rich fluids.

Other contributions

In addition to the above, mention may be made of some findings which are of general import. Leptynites have been shown to be partial melting products of metapelitic precursors; chemical discontinuities, illustrated by frozen magmatic trends were demonstrated to be present between the anorthosites and charnockites of the Chilka lake area; secondary hornblendes were shown to be similar in chemistry to prograde hornblendes but for their lower titanium contents.

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Supriya Mohan Sengupta

Sengupta's contributions to earth sciences comprise studies in several sedimentary basins of India, development of methodology for sedimentological research, and experimental-theoretical investigations of sediment transportation problems.

Studies in sedimentary basins

The geology of the Bengal basin and the Ganga plains lie concealed below thick blankets of river borne alluvium. Through coordinated geological-geophysical investigation Sengupta, as a member of the exploration team of the Standard-Vacuum Oil Company, unravelled the subsurface configuration of a large part of the Bengal basin, identified the tectono-depositional units within this basin, and interpreted the depositional history of the Bengal-Assam region during the Tertiary[1]. He also indicated the possible nature of the subsurface geological structures below parts of the Ganga plains through a review of the available geophysical data[2].

Banerjee and Sengupta's reconnoitory studies on the depositional environments and palaeocurrent system of the Vindhyan sediments[3] led to intensive investigation of these deposits by a number of workers.

In the central Godavari valley, Andhra Pradesh, Sengupta deciphered the depositional environments and palaeocurrent systems of the Kamthi and the associated Gondwana formations. Three distinct members within the Kamthi Formation were identified in course of this work and the stratigraphic equivalent of the Ironstone Shale Formation (named the 'Infra Kamthi' by later workers) was discovered. The stages of shift in the direction of sediment transportation through time, within the Kamthi Formation, were identified[4].

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Sengupta's discovery of uninterrupted fluvial sedimentation from the Uppe Palaeozoic through the Lower Mesozoic in the Godavari valley dispelled the notion of a break in Gondwana sedimentation at the end of the Palaeozoic. Sengupta suggested a model for Gondwana sedimentation through continuous lateral shifting of river channels[4]. Later studies by Bose and Sengupta indicate possible marine influence during deposition of the 'Infra Kamthi' in the Godavari valley[5].

Along with his students Sengupta identified the palaeocurrent systems and deciphered the palaeohydraulic conditions responsible for the Karharbari and Barakar sedimentation in the Giridih basin in Bihar[6].

Methodology for sedimentological research

The orientation and plunge of long axes of elongate pebbles provide clues to the palaeocurrent direction. Sengupta's finding that these parameters vary according to the location of a pebble on a cross-stratified unit led to refinement of the technique commonly used[7].

Rao and Sengupta developed new techniques for sampling and analysis of directional data for palaeocurrent interpretation[8,9].

Investigations on sediment transportation

Flume studies by Kuenen and Sengupta[10] provided insight into the interrelationship between the amount of sediment a stream of water is able to carry in suspension (capacity) and the largest grain-size transported in suspension (competency) by that stream.

Sengupta's flume experiments have shown that the grain-size distribution of the particles carried in suspension by a stream is related to flow velocity, height of suspension, and the nature of the source (bed) material[11,12]. Subsequent studies conducted in collaboration with Ghosh and Mazumder led to identification of the hydrodynamic conditions load may develop as a special case of hyperbolic distribution. These findings have aided in the formulation of methods for (a) computation of suspension load directly from a river bed's grain-size distribution, and (b) estimation of the range in flow parameters from lognormally distributed suspension loads[13,14].

Experiments conducted by Sengupta at Uppsala, and by Ghosh, Mazumder, and Sengupta in a especially designed flume at Calcutta, have led to the finding that *all* the grain-size in suspension are deposited simultaneously when the flow velocity of a stream is reduced[15]. This is contrary to the common belief that the

coarser grains are the first to be deposited. The physical processes responsible for simultaneous deposition of particles of various grain-size are being investigated.

As a Senior Scientist of INSA Sengupta is currently continuing his investigation of sediment transportation problems in fluvial and marine regimes.

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Ram Swaroop Sharma

Sharma has made fundamental contributions in different branches of geology, particularly in the fields of metamorphic petrology, mineralogy and geotectonics of the Precambrian rocks that constitute the Aravalli Mountain and its surrounding areas in Rajasthan State of north-west India.

Metamorphic petrology

In the study of metamorphic rocks it is extremely useful to compare the grade of metamorphism from one place to another. Sharma[1,2] did a pioneering work in mapping metamorphic zones over the entire Precambrian terrane of Rajasthan and demarcated different regions, each characterized by a set of pressure-temperature conditions of metamorphism. With the help of electron microprobe analyses, performed by him during his stay abroad in UK and Germany, Sharma[2,3] analyzed a large number of coexisting minerals in different rock types of the Archaean basement complex, familiarly known as the Banded Gneissic Complex, and of the Proterozoic supracrustals (cover rocks) of the Aravalli and Delhi Supergroups. He made quantitative estimates of the pressure and temperature of recrystallization by thermodynamically deduced geobarometric and geothermometric models.

Sharma[2] also deduced a deformational and metamorphic history of each region by integrating time relations of deformation phases and recrystallization events of minerals in the Precambrian rocks of Rajasthan. Sharma[1,3,4] discovered two distinct regional metamorphic mineral assemblages in the Banded Gneissic Complex, which have become the basis of distinguishing these rocks from the younger Proterozoic cover rocks of the Aravalli and Delhi Supergroups, affected by only one regional metamorphism with local thermal imprints. The polymetamorphic character of the basement rocks is documented for the first time by the discovery of two generations of staurolite, showing different fabric and showing corroded and 'absorbed' outline, and, amongst all, the zoned garnet and

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a garnet rimmed by another garnet, each characterized by different chemical compositions, colour refractive indices and nature of inclusions.

Sharma[2,5,6] made an important discovery of high pressure granulites from north-central Rajasthan. Granulite terranes are found in stable continental cratons and the origin of granulites and charnockites offers a classic petrologic controversy on the relative importance of magmatic processes of dehydration versus influxing of CO_2-rich fluids to dehydrate the deep crust. Geological mapping and a detailed mineralogical and petrological investigations of Sand Mata region by Sharma[2,5] showed that the basic granulites, intercalated with pelitic granulites, had igneous and metasedimentary protoliths. This association was later intruded by norite dykes and granodiorite-charnockite comagmatic series. Because of the dry nature of the protoliths, Sharma[6] argued that no free fluid phase had existed and hence CO_2-influx model was unfavourable for the investigated granulite complex of Sand Mata in Rajasthan.

From mineral chemistry and geothermobarometry, Sharma[2,5] computed pressure and temperature in the range of 7-10 kilobars and 700-850 $\pm$ 50°C. The polymetamorphic granulites from Sand Mata thus revealed a locally high geothermal gradient associated with moderate to high pressures in the region. From these P and T calculations, textural criteria, field relations and available isotopic data, Sharma[2] deduced a P-T-t path for the Sand Mata granulites, which was found to be anticlockwise and hence different from that documented in the geosynclinal sediments involved in regional metamorphism. His research on Sand Mata granulite rocks has focussed on the problem related to the tectono-metamorphic evolution of the region, since the inferred anticlockwise path for these rocks placed considerable constraints, particularly in regard to the applicability of the plate tectonics model for the Precambrian rocks of Rajasthan[2,7].

Mineralogy

Sharma[3,8,10] studied Al-Mg-rich enclaves, especially the gedrite-cordierite-kyanite-sillimanite-bearing rocks, within the Banded Gneissic Complex. He proposed a new mineral reaction: biotite + sillimanite + quartz = gedrite + cordierite + melt, as a follow up reaction, wherein these reactants resulted in the development of the garnet + cordierite bearing assemblages. Sharma[8] located the reaction in an isothermal P-X (Fe-Mg) diagram thermodynamically, thus explaining the formation of 'gedrite-cordierite bearing rocks in high-grade migmatitic terranes in different continental shield areas of the world.

Sharma[10-13] has also reported hitherto unknown mineral assemblages in pelitic and calcareous compositions, particularly kornerupine-staurolite-touramaline - cordierite - kyanite - sillimanite, and wollastonite - scapolite-grossularite-graphite assemblages, indicating an important role of fluid composition during metamorphism in the area. Recently, Sharma[14] has shown by means of mass-balance calculations that corona reactions take place in steps and that boundary migrations in coronitic metagabbros are without volume imbalances. This has been supported by the experimental works in the CFMAS system by David Jenkins and his research team at the State University of New York.

Geotectonics

For the evolutionary mechanism of the Aravalli Mountain, Sharma[7,15] proposed the model of ensialic orogenesis in view of the conclusions arrived at by him from the patterns of metamorphism in the basement and cover rocks as well as from the derived anticlockwise movement path of the polymetamorphosed Sand Mata granulites. According to him a collision between oceanic and continental plates to give rise to this oldest Aravalli Mountain does not find support from P-T-X data base and painstakingly accumulated geological data by him and other land-bound geologists. Sharma emphasised on the inconsistency in the relationship between the required stress pattern for closing the nearly NE-SW trending Aravalli and Delhi basins and the earliest recorded fold axes with the E-W trend in the vast terrain of Rajasthan, lack of any evidence for recognising plates, zones of creation and destruction, shear movement directions, etc., all of which are not favouring the plate tectonics model. His ensialic orogenic model is reported to be more convincing at least for the tectono-metamorphic evolution of the Precambrian rocks of Rajasthan.

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Profiles in Scientific Research: Contributions of the Fellows, Vol-3;
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Bhamidipati Lakshmidhara Kanakadri Somayajulu

Somayajulu has been working on the application of naturally occurring radioactive nuclides to the study of natural processes. This branch of science that involves alloying chemistry and physics with geology and hydrology has become, over the past few decades, an important and integral part of earth sciences. Starting off with the cosmic ray produced radionuclides, ^{10}Be (half-life = 1.5 x 10^6 y) and ^{32}Si (= 140 y), Somayajulu, over the years, used a wide variety of other naturally occurring radionuclides of the non-cosmogenic variety; these belong to the U-Th decay series. These studies were coupled with mineralogical, compositional and, in some cases stable isotope measurements to be able to ascertain not only the time scales of processes but also their nature. He developed simple techniques and made a large enough number of measurements to be able to understand the investigated systems.

Beryllium-10

Somayajulu detected this isotope in the largest authigenic mineral of the ocean, the ferromanganese nodules[1] and showed that the Be-10 dating method is perhaps the most suitable to determine their growth rates which are mostly in the range of 1-10 mm/m.y[2]. In addition, he was involved in the study of ^{10}Be in deep sea sediments to (i) date them, (ii) to understand the past cosmic ray intensity variations and (iii) to detect melt-water inputs into the ocean[3,4]. He also measured ^{10}Be in fall-out (rains) in India as the cosmogenic nuclides are introduced in to the earth mostly in the form of rain and snow. The ^{10}Be studies, with the advent of the Accelerator Mass Spectrometry, a technique which is more than million times more sensitive than the conventional radiochemistry and beta assay of chemically pure Be separated from natural samples, this nuclide is being applied with much success to understand a wide variety of earth processes.

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Silicon-32

This is another cosmogenic nuclide which was measured extensively in the ocean. ^{32}Si concentrations in the ocean are very small and the problem of its measurement in seawater, is, in a way, enormous. For this, an *in situ* extraction technique[5] to extract Si from large volumes (tens of tons) of seawater, and a 4Π type beta counting system to measure feeble (~ 1 count per hour) activities of the ^{32}Si produced ^{32}P were developed. During the Geochemical Ocean Section (GEOSECS) Programme of the IDOE-NSF, the Indian group collected a large number of samples from the world oceans and performed the ^{32}Si measurements in oceans which enabled the use of this radionuclide to study vertical mixing rates and in a comprehensive understanding[6,7] of the marine geochemistry of Si. He also measured this radionuclide in lakes to understand these small fresh water systems which in many ways, behave like the ocean[8].

Uranium

Global U input to the ocean via rivers is very important as U is not only important to understand ocean chemistry but its daughter nuclides have provided a wide variety of techniques to date marine material and to understand some of the oceanic processes. Somayajulu, over the past two decades was intimately associated with this study, i.e. behaviour of U in the estuaries of India and its input to the Bay of Bengal and the Arabian Sea[9].

U-Th decay series nuclides

Notable among these are ^{234}Th (half-life = 24.1 d), ^{230}Th (=75,200 y), ^{226}Ra (=1620 y), ^{228}Ra (= 5.75 y) and ^{210}Pb (=22.3 y), $^{234,230}Th$ in conjunction with $^{238,234}U$ and ^{210}Pb alongwith ^{226}Ra enabled the setting up of time scales of particle reactive processes in the ocean[10,11]. The $^{230}Th/^{234}U$ is an established dating method for both pure[15] and impure marine carbonates of the late Quaternary. Miliolites (impure carbonates) from Saurashtra and Kutch, were extensively dated by the $^{230}Th/^{234}U$ method alongwith ^{14}C, another cosmogenic radionuclide (half-life = 5700 y). The mineralogy, composition and stable isotope systematics of oxygen and carbon to understand the age and origin of these deposits. It should be noted here that the miliolites of Saurashtra and Kutch hold clues to past sea level changes, neotectonics and the emergence of paleolithic man in that region. The studies of Somayajulu and co-workers have helped in no small way to understand these aspects[13]. Marine sediments have been dated extensively, deep sea deposits using ^{230}Th and the near-coastal ones using ^{210}Pb. There are standard techniques that have been employed on near-coastal and deep sea sediments with a view to

understand the recent (few centuries) and the late Quaternary paleoclimates[14]. He also studied magnetic susceptibility stratigraphy of Ocean Sediment Cores[15] non-destructively, which will help in identifying horizons of large variations indicating important past changes. This study has become an important part of the International Geosphere Biosphere Programme in which Somayajulu and his group are actively involved presently.

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Mandakolathor Subramanya Srinivasan

As initiator and leader of a team of workers on the Neogene bio- and chronostratigraphy, Srinivasan has made significant contribution to the Late Cenozoic oceanic biostratigraphy and planktonic foraminifera. His work has been concerned mainly with the Neogene stratigraphy of Andaman-Nicobar islands, Late Cenozoic planktonic foraminiferal biochronology of the south-west Pacific and Indian Ocean deep sea cores, their correlation, systematics of Neogene foraminifera and in the area of Paleoceanography. Major techniques include the utilization of marine microfossils, stable isotopes and marine sediments.

Andaman-Nicobar islands

By examining a large number of overlapping sections exposed on these islands, Srinivasan has been able to produce an almost complete Late Cenozoic sequences of low-latitude planktonic foraminiferal zones[1,2]. He further established new methods of meaningful subdivision of the thick monotonous sequences[3]. The sequences on Andaman-Nicobar islands are important because of their strategic position in the Northern Indian Ocean, an area where few other good Neogene marine sequences exist, except for the Deep Sea Drilling Programme (DSDP)and Ocean Drilling Programme (ODP) sections. One of the most interesting observations made during the study was to record a close relationship among volcanism, geomagnetic reversals, microfaunal turnover and volcanically induced climatic changes. The contributions made provide necessary data for detailed time-slice studies on the Indo-Pacific deep sea cores. The studies have further provided basic data of fundamental importance in the hydrocarbon exploration in the Andaman Basin.

Neogene planktonic foraminifera

Standardized and relatively complete taxonomies are a basic requirement as well as a highly significant result of Paleoceanography programme. Contributions of

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Srinivasan on the Neogene planktonic foraminiferal biochronology have provided a basic clue to the study of the evolutionary trends in this group, which is vital to the understanding of marine sediments throughout the world. For the first time classification of the group has been treated in a totally phylogenetic or natural order[4,5]. In a long term view and also in the immediate future, this type of study would enable stratigraphers to conduct inter-regional correlation and dating of Neogene deep sea sediments. The scanning electron microscope (SEM) has been centrally employed in these studies, which has added much to our understanding of the surface ultrastructure within the planktonic foraminifera. This in turn, has provided a crucial insight into the complex evolution and paleoceanography of the group. SEM studies conducted by Srinivasan and Kennett[6-8] indicate that ultrastructural change consistently with changing latitudes and reflect a close relationship with water masses.

An extensive study conducted on all the Neogene planktonic foraminifera from tropical to polar regions using deep sea cores of the Deep Sea Drilling Project (DSDP) has resulted in the book *Neogene planktonic foraminifera: A phylogenetic atlas*[5]. This volume represents a synthesis of the evolution of planktonic foraminifera during the last 25 million years of earth's history for the entire world's ocean.

In addition Srinivasan has made important contributions in respect of the problems of Cenozoic epoch boundaries such as Eocene/Oligocene boundary[9], Oligocene/Miocene boundary[10], Micoene/Pliocene boundary and Pliocene/ Pleistocene boundary[11-13] based on massive new data on the evolutionary changes in planktonic foraminifera over the boundary and the changes in the character of the assemblages.

Paleoceanography

Hydraulic piston corer (HPC) developed by the deep sea drilling project has provided an unprecedented opportunity to examine deep sea cores across wide ranging latitudes through the Cenozoic. As a member of the scientific team on board the D/V *Glomar Challenger* Leg 90 Srinivasan has carried out detailed time series studies to gain a better understanding of the evolution of the oceans, their circulation, water mass distribution, variability and vertical structure through the late Cenozoic in the south-west Pacific region.

A combination of paleomagnetic, stable isotopic and biostratigraphic stratigraphies in hydraulic piston cores with a resolution of few thousand years, allow examination of how the biostratigraphic schemes correlate from low to high

latitudes and from Indian Ocean to south-west Pacific and determination of the most valuable datum levels for planktonic microfossil groups during the Late Cenozoic[12].

Current research and future programmes

One of Srinivasan's ongoing studies pertaining to northern Indian Ocean paleocirculation history is related to deep sea circulation, which in turn reflects benthic foraminiferal distribution. Deep sea benthic foraminifera have been found to be associated with distinct water masses in various parts of the oceans. Initially, these investigations were carried out in the north Atlantic and south Pacific. Efforts are now made to carry out detailed studies on the Neogene benthic foraminifera in the Indian Ocean. A detailed analyses of deep sea benthic foraminiferal diversity is currently underway to gain a better understanding of the history of bottom/deep water circulation patterns, rate of sedimentation, and nature of deep sea hiatuses during the Cenozoic. A substantial part of the Neogene benthic foraminiferal taxonomy of the Indian Ocean has been completed by Srinivasan and coworkers and will be ready to go to press in 1995.

Further Srinivasan is also working on a project aimed at drawing together a large volume of information on multiple microfossil biostratigraphy of the Indian Ocean and the south-west Pacific Ocean of the late Cenozoic. The objective of this investigation is not only to collate the numerous biostratigraphic schemes now available for the region as a result of deep sea drilling, but to detect the intervals of major biogeographic events that occurred during the Late Cenozoic and to attempt to relate these to paleoceanographic changes.

Future programmes

Recent major thrusts in the study of paleoceanography by Srinivasan include studies on the tempos and modes of paleoceanographic changes over time scale ranging from just a few thousand years to those over tens of millions of years. This research is aimed at understanding as to how ocean climate, circulation and fertility have changed through time.

In the coming years, Srinivasan and his coworkers proposed to focus their efforts primarily on the Miocene, a time of major ice build-up on the Antarctica and one of the major steps in oceanic and climatic evolution. This study would provide a better understanding of the evolutionary steps by reconstructing the oceanography of the relatively stable time just preceding and following the Middle Miocene ice-cap build up on the Antarctica, and by tracing the oceanographic changes from one time slice, or evolutionary stage, through the

next by studying several detailed time-series. Biostratigraphic and isotopic data are now being compiled for these intervals.

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Khadg Singh Valdiya

Placing Kumaun Himalaya in the focus of attention, Valdiya has been probing this geodynamically crucial and responsive segment of the mountain are, consistently for over 35 years. Regional in dimension and holistic in character, his studies encompass stratigraphical, sedimentological, tectonic and environmental aspects of the orogenic province that is rising up fast and rejuvenating itself geomorphically. Having a penchant for nonconformism, Valdiya has been making radical, often controversial postulations—most of which have now received wide or universal acceptance. His environmental investigations embrace three aspects—natural hazards related to landslides and groundsubsidence, earthquakes in zones of active faults, and diminishing discharges of mountain springs.

Neotectonics of active faults

The much-faulted terrain of the Lesser Himalaya, characterized by many active faults, evinces unmistakable tendency of rising up[1,2] at a fast rate between 1 and 5 mm/yr. This is quite evident from eloquent signs of geomorphic rejuvenation of the once mature terrain, deflection and offsetting of drainage, and development of landforms unique to neotectonically active belts[3-5]. As a matter of fact, until the Neolithic times in the mid-Holocene, the populated Lesser Himalaya was a gentle terrain of low relief less than a few hundred metres above sea-level, so that the Stone-Age people freely migrated north and south across the Himalayan domain[1,2]. Uplifts, subsidence and displacement of deposits of lakes, rivers and landslides straddling across faults and fault zones, and drainage deflections demonstrate that the crust-cutting thrusts that define the boundaries of the various Himalayan terrains (belts), and the majority of transverse and oblique faults tearing the terrains have registered episodic movements of the order of 20 to 40 m (even as much as 325 m) in the vertical direction and 4 to 12 km in the

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horizontal[2,4-7]. The transverse faults are found to the loci of movements generating earthquakes, and the NNW-SSE trending ones are comparatively more active[4].

The cumulative effect of recurrent though intermittent movements on active faults in the Quaternary period is the development of the formidable mountain barriers and forbiddingly rugged topography, the blocking of streams and rivers and resultant formation of lakes in the Siwalik and Outer Lesser Himalayan belts, and their rapid filling with sediments and eventual obliteration[2,4,5,8].

Tectonics of India-Asia collision

Studies carried out in the Tethys and Great Himalaya domains in the north demonstrated far-reaching impact of collision of the Indian and Asian continental plates. In sharp disagreement with others, Valdiya[7,9] concluded that the Indian plate instead of sliding under Tibet (Asian plate), buoyed up and got buckled into domal upwarps along its leading edge immediately south of the zone of collision, and broke up along intracrustal faults in its hind part following the blocking of plate movement in the suture zone. Doming up of the Precambrian basement crystallines of the leading edge, the high heat-flow manifest in high geothermal gradient myriads of hot springs, extensive generation of granitic melt, and existence of high-conductivity layer in the upper part, and the deepening of the crust-mantle boundary towards the zone of collision, have been interpreted by Valdiya to imply buoyancy resistance encountered by the northward-drifting Indian plate. The splitting of the crust along the base of the upper crust and along the contact of basement-cover sediments gave rise to the Main Central Thrust (MCT) and the Trans-Himadri Fault (T-HF), respectively[7,9].

At variance with the commonly held perception, Valdiya[3,7,10] relocates the boundary between the Great Himalaya and Lesser Himalaya—the Vaikrita Thrust or the redefined Main Central Thrust (MCT)—and recognizes it as an archetypal intraplate subduction zone, characterized by thrust duplex resulting from repeated movements in piggy-back style. The basement rocks—designated as the Vaikata Group—underwent strong metamorphism at temperatures 600-650°C and pressures more than 5 kb, and pervasive migmatization associated with 28-18 my old granites formed by differential melting of the Vaikrita rocks at 15-20 km depth during the acme of thrust deformation[7].

Delimited by the MCT and Main Boundary Thrust (MBT), the Lesser Himalaya comprises complexly folded succession of Proterozoic sedimentary rocks, thrust over by great piles of metamorphics intimately associated with highly sheared and pervasively milled porphyritic granites 1900 $\pm$ 100 my in age, and intruded by the 560 $\pm$ 20 my old granites marking Pan-African or Cadomian orogeny towards the close of Lower Cambrian Times[3,7,11]. Embracing syclinorial Krol Nappe, the southern front of the Lesser Himalaya is riven with transverse tear faults and the longitudinal faults developed along crestal planes giving rise to horsts and grabens of sorts and tectonic lakes, and triggering landslide on all sides of the uplifted massifs[3,4].

Stratigraphic order

Valdiya's[12,13] first-over systematic study of algal-bacterial built stromatolites led to fixing of precise ages of the unfossiliferous but crucial rock-formations of the Lesser Himalaya and their correlation with those of the Vindhyan Basin[13]. What were earlier regarded as Permo-Triassic (270-180 mc) in age, were pushed down to the Riphean or Upper Proterozoic (1300-900 my)—a deduction that has now been substantiated by radiometric dating of associated rocks and by recent discoveries of reliable fossils in the topmost horizon. Valdiya's[12] assignment of the Mandhali Formation of the Calc Zone of Tejam (Pithoragarh) to the Cambro-Ordovician has been corroborated by lower Cambrian fossils recently discovered in the homotaxial Tal.

Pattern of sedimentation and palaeogeography

Comprehensive sedimentological study of the early Middle Proterozoic flysch assemblage in Himachal Pradesh and Garhwal, encompassing first-ever palaeocurrent investigation in the Himalaya, showed prevalence of turbidity currents, and demonstrated that the Lesser Himalayan sediments were derived not from the north as then understood but from the Aravalli mountain in Peninsular India, and that the slope of northern India was then northwards[14]. Later studies[11] showed that the palaeoslope and palaeocurrent directions remained the same throughout the Later Proterozoic times—until sedimentation came to the end towards the close of the Lower Cambrian.

Hydrogeology of mountain springs

Comprehensive hydrogeological study of springs in the catchment of the Gaula river in south-central Kumaun—in which a major dam is proposed—showed that

deforestation, road-building and drastic changes in landuse pattern have seriously affected the hydrological regime in about 40% of the villages of the catchment, manifest in drying up of some springs and reduced (9.7-76%) discharges in others[8]. Consequently, there has been decline in the flow of the Gaula river—the discharge came down by 29.2% between 1951-1960 and 1961-1970 and by 38.5% between 1971 and 1981. Similar trend is evident in the catchment of the KhulGad, a tributory of the Kosi river in central Kumaun.

Erosion and landslides

Investigations on accelerated erosion and landslides in the zones of active faults and thrusts have helped in hazard-zone mapping and formulating strategy for development programme—including urbanization in the basin—in the context of the management of environment of the Kumaun Himalaya[14,15].

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Veeravalli Venkata Ranga Varadachari

Varadachari, a leading physical oceanographer of India, has been responsible for formulating research programmes and organizing cruise programmes in the field of physical oceanography in India since the International Indian Ocean Expedition (1962-65). Right from the inception of the National Institute of Oceanography (NIO), on 1 January 1966, he has been organizing studies in physical oceanography, as the Head of the Physical Oceanography Division of NIO and later as its Director.

Varadachari's main contributions are in the areas of upwelling, ocean currents, watermasses, submarine canyons, coastal zone management and the impact of oceans on the Indian south-west monsoon. He employed some new techniques. such as vertical time sections, etc., for studies on upwelling and sinking, and studied the physical and dynamical aspects of upwelling along the Indian coastline. He developed a new theory on coastal currents as a factor in inducing upwelling[1]. The theory has been found useful in explaining upwelling not only along the Indian coastline but also along the other coasts in the Indian Ocean region, such as the Somali Coast. He has studied the vergence field in the North Indian Ocean in order to locate the upwelling and sinking regions in the area in different seasons[2]. He has also studied the surface circulation in the North Indian Ocean[3,4]. He identified and surveyed the watermasses of the Red Sea and the Persian Gulf origin in the Bay of Bengal[5]. Several submarine canyons off the east coast of India were located and surveyed by him[6]. His studies on the thermal structure in the Arabian Sea have contributed to an understanding of the dynamics of the southwest monsoon[7].

The other area in which Varadachari has done significant work is coastal zone management. Beach erosion problems along the Indian coastline have been studied, particularly along the coasts of Kerala and Goa. Beach evolution was studied in response to waves, tides, winds, currents, etc.[8-11]. Problems of

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sedimentation in harbours, rip currents off beaches, formation of sand bars near river mouths and formation of mud banks in the nearshore regions were investigated[12-15]. Under his Directorship (1981-1985), NIO made significant contributions in the field of marine science. It played a key role in organizing the first, second, third and fourth Indian Scientific Expeditions to the Antarctica, in 1981, 1982, 1983 and 1984 respectively. India has received the status of 'Pioneer Investor' in the Survey of 'polymetallic nodules' in the Indian Ocean, based on the work carried out by NIO, mainly during his Directorship. NIO has rendered services to several governmental and industrial agencies in the country in the vital fields of development of ports and harbours and offshore oilfields, effluent disposal, development and protection of coastal zone, etc.

Varadachari, as Vice-Chairman of the Committee on Climatic Changes and the Ocean (CCCO) of the Scientific Committee on Oceanic Research (SCOR) and the Intergovernmental Oceanographic Commission (IOC), contributed to the planning and formulation of the global experiments, such as the Tropical Ocean and the Global Atmosphere Programme (TOGA) and the World Ocean Circulation Experiments (WOCE).

He has initiated at NIO programmes of research in the areas of application of remote sensing to oceans, oceanic modelling, etc., with the aim of developing facilities for the prediction of marine environment and climatic changes. Some of the other major areas of ocean research which were initiated or which received impetus under his Directorship of NIO are minerals from the sea, food from the sea, organic chemicals from the sea, energy from the sea, deep sea biology, study of the Antarctic Ocean, etc.

Varadachari, who started his career as a teacher at postgraduate level in Meteorology and Oceanography at the Andhra University, in 1949, also made significant contributions to teaching and formulation of marine science programmes in several Indian universities having postgraduate course in physical oceanography and meteorology.

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(Sectional Committeewise)

SECTIONAL COMMITTEE — VI

SECTIONAL COMMITTEE — IX

Alphabetical Index

Name	SC	Vol	PP	Name	SC	Vol	PP
Biswas SN	2	1	231	Das HK	9	5	2372
Biswas S	2	1	234	Das J	4	3	1077
Bomford G	5	3	1318	Das J	9	5	2365
Bose A	2	1	240	Das MR	9	5	2379
Bose AK	3	2	630	Das PK	5	3	1323
Bose MK	5	3	1319	Dasannacharya BA	2	1	279
Bose MN	6	4	1589	Dass CMS	7	4	1855
Burma DP	9	5	2350	Datta A	9	5	2390
Buti B	2	1	245	Datta AG	9	5	2395
Chadha MS	3	2	636	Datta K	7	4	1859
Chakravarti R	4	3	1063	Datta Munshi JS	7	4	1863
Chakravarti RN	3	2	641	Dattagupta S	2	1	283
Chakravarti RN	8	5	2077	De R	10	5	2578
Chakravorty A	3	2	648	Deb BM	3	2	677
Chakravorty D	4	3	1070	Deekshatulu BL	4	3	1080
Chakravorty M	9	5	2355	Deo MG	8	5	2085
Chandrasekaran S	3	2	653	Deshpande BG	5	3	1330
Chandrasekhar S	2	1	248	Desikachary TV	6	4	1598
Chandrashekaran MK	7	4	1851	Dey AK	5	3	1334
Chatterjea JN	3	2	657	Dhar MM	3	2	684
Chatterjee (Mrs) A	3	2	661	Dhar ML	3	2	688
Chatterjee SD	2	1	249	Dhawan BN	8	5	2091
Chatterjee SN	9	5	2359	Dinesh Mohan	4	3	1085
Chattoraj DK	3	2	665	Dogra PD	10	5	2581
Chidambaram R	2	1	252	Dominic CJ	7	4	1872
Chitre SM	2	1	257	Dumir VC	1	1	15
Chopra KL	2	1	265	Dutta AK	2	1	288
Chopra VL	6	4	1593	Dutta GP	7	4	1878
Choudhary B	10	5	2575	Dutta Majumdar DK	4	3	1090
Chowdhury AB	8	5	2080	Dutta Roy SC	4	3	1095
Chowdhury M	3	2	670	Gadagkar R	7	4	1883
Dani SG	1	1	10	Gadgil MD	10	5	2587
Daniel RR	2	1	271	Ganapathi K	9	5	2399
Das BN	4	3	1073	Gandhi RP	3	2	691
Das Gupta MK	2	1	275	Gangal SG	8	5	2098
Das Gupta NM	9	5	2386	Ganguli HC	8	5	2106
Das Gupta S	1	1	11	Ganguli NC	10	5	2591

Name	SC	Vol	PP	Name	SC	Vol	PP
Kesavan PC	6	4	1640	Manna GK	7	4	1915
Kessar SV	3	2	780	Manoharan PT	3	2	813
Khan AM	10	5	2632	Mashelkar RA	4	3	1139
Khan MMT	3	2	785	Mathews PM	2	1	386
Khanna-Chopra R	10	5	2639	Mathur KS	8	5	2145
Khera AS	10	5	2644	Meher-Homiji VM	6	4	1669
Khetrapal CL	3	2	792	Mehrotra KN	7	4	1923
Khoshoo TN	6	4	1645	Mehrotra RC	3	2	819
Khush GS	10	5	2648	Menon KKG	9	5	2459
Kochupillai N	8	5	2132	Menon MGK	2	1	391
Koteswaram P	5	3	1370	Merh SS	5	3	1384
Kothari LS	2	1	336	Mishra RS	1	1	65
Krishan Lal	2	1	340	Mishra SK	5	3	1386
Krishna P	2	1	346	Misra R	6	4	1674
Krishan RS	2	1	350	Misra RC	5	3	1390
Krishna J	4	3	1116	Mitra AP	2	1	395
Krishnamurthy SS	3	2	798	Mitra AN	2	1	400
Krishnan R	4	3	1120	Mitra SK	1	1	71
Krishnan V	3	2	803	Modi VV	10	5	2653
Kulkarni AB	3	2	807	Mohan Ram HY	6	4	1678
Kulkarni BD	4	3	1124	Mookherjee A	5	3	1393
Kumar HD	6	4	1651	Moudgal NR	9	5	2468
Kumar N	2	1	355	Mukherjee AS	7	4	1929
Kumar R	4	3	1132	Mukherjee D	3	2	823
Kundu DN	2	1	359	Mukherjee SK	10	5	2657
Lakhanpal RN	6	4	1657	Mukherjee SK	10	5	2662
Lakshmanan M	2	1	366	Mukherjee SK	8	5	2148
Lal D	2	1	370	Mukhopadhyay D	5	3	1396
Laumas KR	8	5	2137	Mukunda N	1	1	76
Lawande SV	2	1	376	Munjal ML	4	3	1144
Luthra (Mrs) UK	8	5	2142	Murty BR	10	5	2664
Maitra PK	9	5	2451	Muthukkaruppan VR	7	4	1934
Majumdar CK	2	1	382	Nadkarni MG	1	1	80
Malik CP	6	4	1663	Nag B	2	1	406
Malik SK	1	1	60	Nag K	3	2	826
Mandal NC	9	5	2454	Nagarajan K	3	2	831
Mani Anna	5	3	1381	Naha K	5	3	1401

Name	SC	Vol	PP	Name	SC	Vol	PP
Ramanan S	1	1	132	Roy AB	5	3	1451
Ramaniah MV	3	2	905	Roy DP	2	1	494
Ramanna R	2	1	460	Roy P	2	1	501
Ramasarma T	9	5	2495	Roy RP	6	4	1728
Ramaseshan S	2	1	463	Roy S	5	3	1447
Ramaswamy GS	4	3	1208	Rudraiah N	1	1	139
Ranadive (Mrs) KJ	8	5	2184	Sachdev PL	1	1	145
Randhawa HS	8	5	2192	Saha AK	5	3	1456
Randhawa NS	10	5	2685	Saha NK	2	1	506
Ranganathan S	3	2	911	Sahni A	5	3	1459
Ranganathan S	4	3	1213	Saidapur SK	7	4	1981
Rangaswami S	3	2	919	Sandhu SS	3	2	960
Rangaswamy NS	6	4	1721	Sane PV	6	4	1733
Rao AR	7	4	1975	Santappa M	3	2	963
Rao BR	2	1	471	Sanyal GS	4	3	1240
Rao CNR	3	2	924	Sanyal SC	8	5	2214
Rao CR	1	1	135	Sarkar JK	8	5	2224
Rao KJ	3	2	930	Sarkar SN	5	3	1464
Rao KR	2	1	484	Sarma VVS	4	3	1243
Rao NGP	10	5	2690	Sarma YSRK	6	4	1738
Rao PR	4	3	1218	Sasisekharan V	9	5	2507
Rao PR	4	3	1229	Sastri MVC	3	2	969
Rao PS	3	2	939	Sastri VV	5	3	1478
Rao PVS	4	3	1223	Sastry PS	9	5	2512
Rao SRV	7	4	1971	Sathyamurthy N	3	2	974
Rao UR	2	1	489	Sathyanesan AG	7	4	1985
Rao VSR	9	5	2501	Saxena PN	8	5	2227
Rastogi RG	5	3	1441	Seal SC	8	5	2234
Rastogi RP	3	2	944	Sekhon GS	10	5	2706
Ray AP	8	5	2199	Sen AB	8	5	2240
Raychadhuri SP	10	5	2696	Sen HG	8	5	2243
Reddy CRRM	8	5	2206	Sen PK	8	5	2248
Reddy GKN	3	2	951	Sen SN	5	3	1482
Reddy GM	10	5	2700	Sen SK	5	3	1485
Reddy VU	4	3	1234	Sen SK	6	4	1742
Rohatgi-Mukherjee KK	3	2	954	Sen SP	6	4	1746
Roy A	5	3	1444	Sengupta P	3	2	977

Name	SC	Vol	PP
Thirumalachar MJ	6	4	1817
Thiruvenkatachar VR	1	1	189
Thomas J	9	5	2538
Thosar BV	2	1	544
Trehan SK	1	1	194
Trivedi BS	6	4	1822
Udgaonkar BM	2	1	547
Udupa HVK	4	3	1269
Uppal HL	4	3	1275
Vaidya PC	1	1	196
Vaidyanath LR	4	3	1279
Vaidyanathan CS	9	5	2543
Valdiya KS	5	3	1506
Valiathan MVS	8	5	2312
Varadachari VVR	5	3	1511
Varma RK	2	1	551
Venkataraman G	2	1	557
Venkataraman GS	6	4	1825
Venkatesh YV	4	3	1283
Venkateswarlu P	2	1	560
Venkoba Rao A	8	5	2315
Verma AR	2	1	567
Verma JP	6	4	1829
Vig OP	3	2	1010
Vijayan M	9	5	2548
Vijayaraghavan R	2	1	571
Virk DS	10	5	2756
Wadia NH	8	5	2319
Yadava JNS	10	5	2750